Seismic site response estimation in the near source region of the 2009 L'Aquila, Italy, Earthquake

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ABSTRACT:
To better estimate the seismic ground motion during the April 6th, 2009 earthquake in L'Aquila, we deployed temporary arrays in the near-source region. Several arrays have been successively set up in the Aterno valley's epicentral area and have recorded the aftershocks that followed the main shock, between April and September. The data has been processed in order to study the spectral ratios of the horizontal component of ground motion at the soil site and at a reference site, as well as the spectral ratio of the horizontal and the vertical movement at a single recording site. The results obtained confirm the presence of large amplification effects in both L'Aquila's historic centre and in the suburban areas. The resonance frequency has been found to be close to 0.6 Hz in downtown L'Aquila whereas the suburban areas show amplification at frequencies ranging from 2 Hz to 5 Hz.

Keywords: L'Aquila earthquake, site effects, strong motion

1. INTRODUCTION

On the 6th of April, 2009 at 3:32 local time, a Mw 6.3 earthquake hit the Abruzzo region (central Italy) causing more than 300 casualties. The epicenter of the earthquake was 95km NE of Rome and 10km from the centre of the city of L'Aquila, the administrative capital of the Abruzzo region. This city has a population of about 70,000 and was severely damaged by the earthquake, the total cost of the buildings damage being estimated around 3 Bn €. Historical masonry buildings particularly suffered from the seismic shaking, but some reinforced concrete structures from more modern construction were also heavily damaged. During the earthquake the damage level reached a maximum in the Aterno valley, were L'Aquila is located, as well as in the Poggio di Roio area and in the village of Catelnuovo (Fig. 1). The damage distribution could be linked to geological and topographical site effects.

To better estimate the strong ground motion during the earthquake, we deployed temporary arrays in the near source region. The installation was carried out by several research institutions including Istituto Nazionale di Geofisica e Vulcanologia (Itlay), Università della Basilicata (Italy), GFZ-Potsdam (Potsdam, Germany) and CETE-Mediterranée (Nice, France) (e.g. Fig. 2). We put seismological stations in the middle Aterno valley, in the municipal territory of L'Aquila and in the neighbouring municipalities (upper Aterno valley) (Fig. 3). We also monitored a rural quarter composed of ancient villages located right above the hypocenter, on the Roio plateau where the damage distribution was not homogenous. The stations have been installed nearby or inside the most damaged centers, where the macroseismic intensity reached the IX/X MCS degree (Galli et al., 2009) and where coseismic surface effects have been observed (Emergeo Working Group, 2010). In total, more than 100 sites have been monitored using accelerometers and velocimeters during several field campaigns (Fig. 3). The seismic stations have been equipped with velocimeters and/or accelerometers (Le3d-5s, Le3d-1s, MarkL4c3d and Episensor) coupled with digitizers (Reftek R72A and R130, EDL, Ageocodagis Kephren) or with integrated digitizer/accelerometer systems (Kinemetrics K2 or ETNA). In most of the case, the energy has been supplied to the station by means of solar pannels and the time accuracy is guaranteed by GPS antenna connection. The accelerometric and velocimetric seismic station have been installed in free-field or inside buildings. In particular, the accelerometric sensors have been used in order to record the larger aftershocks without any signal saturation and to evaluate the possible presence of non-linear effects.

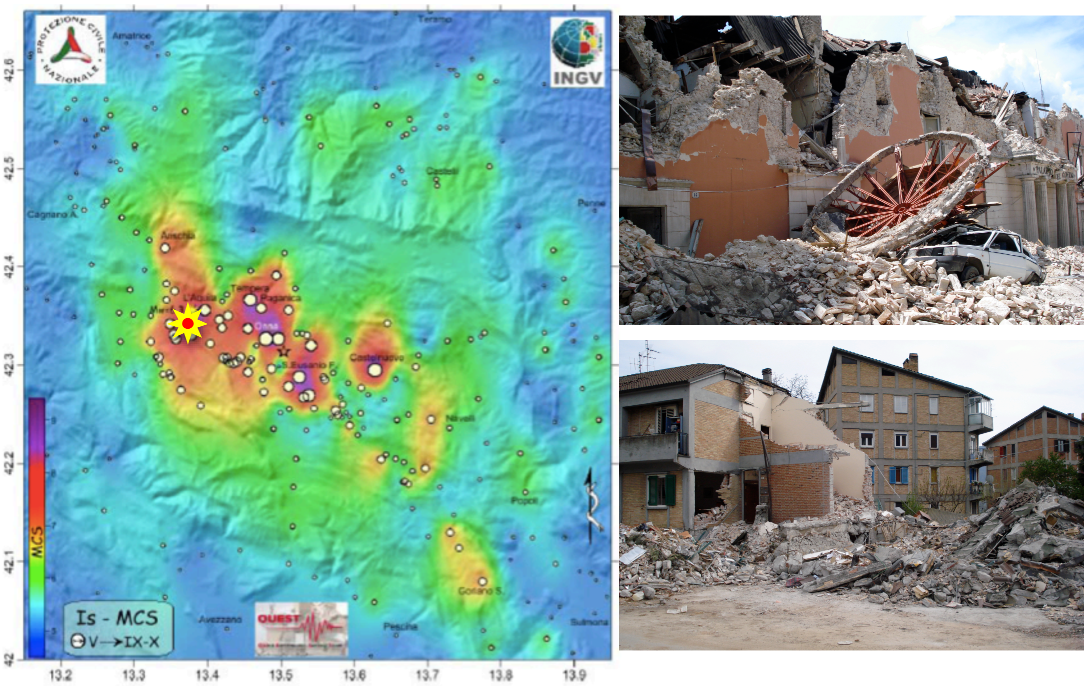

Figure 1. Left :Macroseismic intensities (MCS) distribution of the April 6th, 2009 earthquake (Galli and Camassi, 2009). The map has been obtained by interpolation of the punctual intensity observation. The yellow star shows the position of the instrumental epicenter. Right : collapsed building in L'Aquila.

Figure 2. Example of stations set up in L'Aquila by CETE Méditerranée team.

The soil's fundamental resonance frequency can be evaluated on the field, thanks to various methods. Experimental methods are commonly based on the recording of surface vibration due to earthquake or ambient noise. In the case of earthquake data, the recordings on a soil site are compared to the ones at a rocky station by computing spectral ratios. The ambient noise data is used to compute H/V spectral ratios.

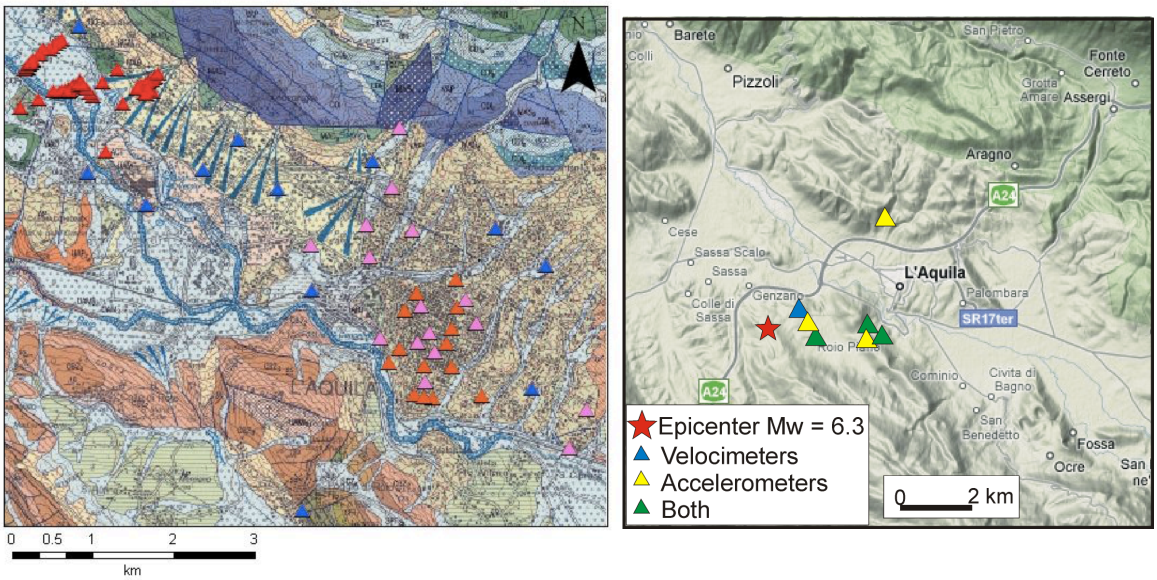

Figure 3. Temporary seismological stations installed in the Aterno valley (left) and around Roio Piano (right) during the L'Aquila 2009 earthquake sequence.

The earthquake sequence of 2009 happened in the central Apennines in an extensional tectonic regime context with prevalent SW-NE direction that has been shaping the region since the mid-Pliocene (Pace et al., 2006). This tectonic regime is in particular at the origin of NW-SE oriented basin aperture such as the Aterno river valley. The deposits filling the valley are dated from Middle Pleistocene to present and are formed by alternations of calcareous silt, gravel and conglomerate layers. Coarse debris deposits heterogeneously recovered the top of these layers.

L'Aquila's historical center is set on a Quaternary fluvial terrace (breccias with limestone boulders and clasts in a marly matrix), which forms the left bank of the Aterno River and slopes down in a southwest direction towards the Aterno River. The alluvial are lying on lacustrine sediment reaching their maximum thickness (about 250m) in the centre of L'Aquila. After De Luca et al. (2005), these quaternary deposits seem to lead in an important amplification factor in the low frequency range (0.5-0.6 Hz). However, the level of amplification varies strongly from one point to another in the city center.

2. SEISMIC NOISE RECORDINGS ANALYSIS

2.1. Methodology

A method based on microtremor was introduced in Japan for estimating dynamic characteristics of surface layers, in early 1970 (Nogoshi and Igarashi, 1971). After an English paper by Nakamura (Nakamura, 1989), many people paid a renewed attention to this technique of estimating dynamic ground characteristics, since clear and reliable information was provided by very simple and inexpensive noise measurements. In recent years, the theoretical background of the method has been studied (see for instance the SESAME project) and there have been many successful experimental studies based on it.
The principle of the method consists of recording the ambient vibrations according to 3 directions (a

vertical, and two horizontals). Signals are processed numerically to obtain the corresponding Fourier spectra. The horizontal spectra are then divided by the spectrum of the vertical component. This ratio (HVNSR) computation results in a curve that presents a peak corresponding to the site fundamental resonance frequency. It is the frequency below which there is no amplification of the surface ground movement during seismic action.

2.2. Results

The data processing has been done using the SESARRAY software developed in the frame of the SESAME European project (Wathelet, 2005). The FFT have been computed considering several 60 second long windows of stationary signal, allowing us to compute the HVNSR down to 0.2 Hz. Their selections are completed using the ratio computation of the short-term-average (STA) over the long-term-average (LTA). Usually, noise signal is considered to be stationary when this ratio lies between 0.3 and 2. The spectrum smoothing is done with the Konno and Ohmachi (1998) smoothing technique. This method is recommended by SESAME guidelines (SEASME, 2004) as it accounts for the different number of points at low frequencies.

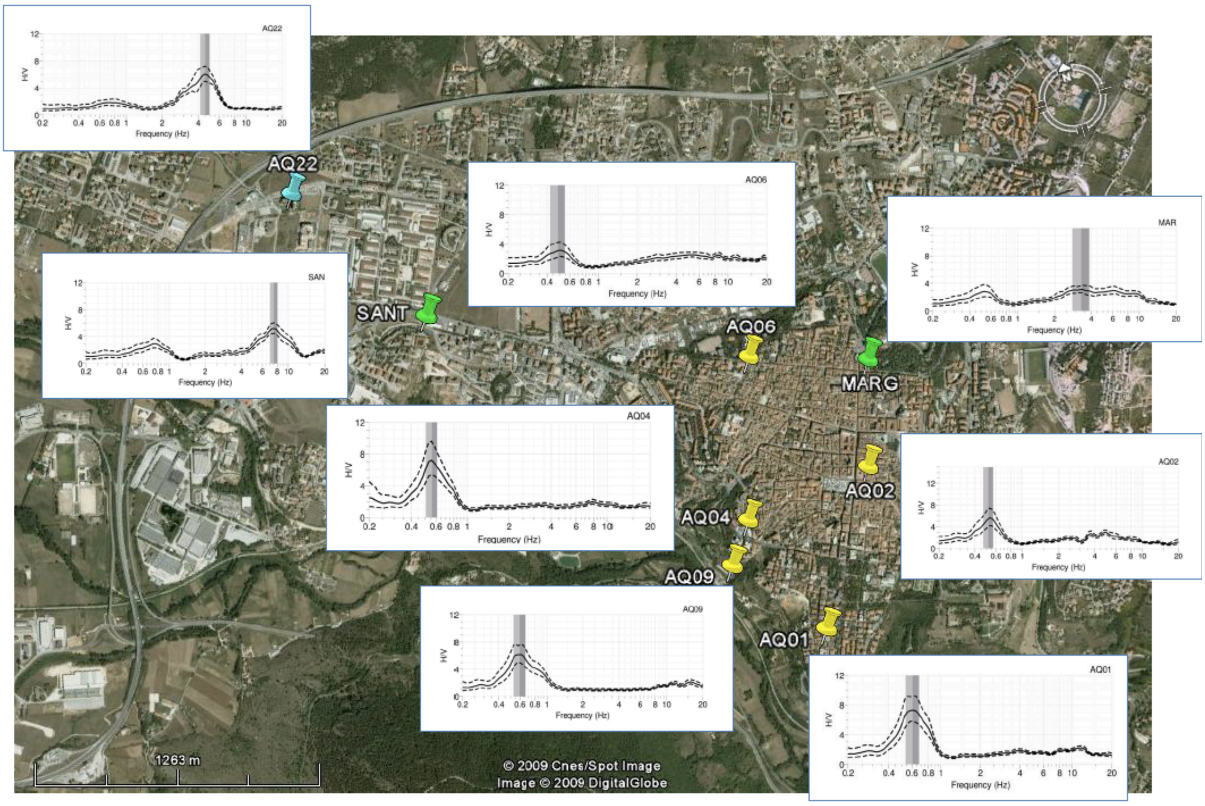

Figure 4. Some H/V curves obtained at stations in L'Aquila.

In L'Aquila's historic center, the H/V spectral ratios on ambient vibration recordings exhibit a low resonance frequency at about 0.5 Hz (Fig.4). However, the ratio maximum at this frequency differs from the North to the South of the city center. Outside the city limits, if the 0.5 Hz peak can still be observed, a higher frequency peak generally dominates (4 Hz to 8 Hz).

Fig. 5 presents the resonance frequencies we derived from the HVNSR analysis in the Aterno valley. We observe that this frequency is increasing from L'Aquila downtown to the Northwest and from the center of the valley to the edges. The stations on the border of the valley such as the one installed close to the San Giuliano monastery or the one in Poggio di Roio exhibit flat HVNSR curves between 0.2 Hz and 20 Hz. On these sites, no site effects are thus suspected.

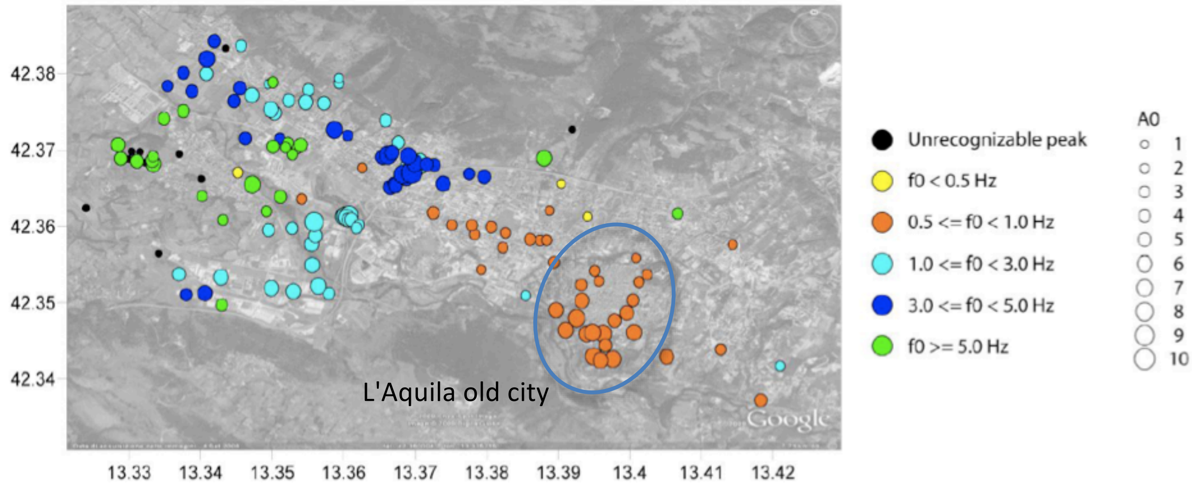

Figure 5. Resonance frequency inferred from the HVNSR in the Aterno valley.

3. AFTERCHOCK RECORDINGS ANALYSIS

3.1. Methodology

Borcherdt and Gibbs described this technique for the first time in 1970. It consists of recording earthquakes on various sites suspected of seismic amplification and comparing the gathered data with simultaneous recordings at a reference station placed directly on a flat-outcropped rock. The acquired signals are processed numerically to obtain their Fourier spectrum and the ratio site-over-reference (called also Standard Spectral Ratio, SSR) is then computed.

For a given place, these spectral ratios are function of the earthquake source. According to Field and Jacob (1995), reliable results are only obtained considering a mean of several spectral ratios computed from a significant number of well-distributed earthquakes over a large magnitude and distance range. When this condition is full-filled, the mean spectral ratio can be considered as an estimated transfer function of the investigated site.

The main difficulty of the method lies in the choice of the reference station. The critical assumption made is that the surface rock-site record used as a reference is equivalent to the input motion at the base of the soil layers. However, surface rock-site can have a site response of its own, which could lead to an underestimation of the seismic hazard when these sites are used as reference sites (Steidl et al., 1996). Several sites among the monitored locations are considered here as reference stations: San Giuliano, Cansatessa and Pescomaggiore to the north (located on limestone), Roio di Poggio (on limestone), Civita di Bagno, Fossa and Stiffe to the south (on cemented conglomerates). On these sites the HVSRN appeared to be flat enough for them to be considered as references.

3.2. Results

Since May 27th 2009, 37 seismic stations have been recording the aftershocks inside and outside the historical center of L'Aquila. About 300 earthquakes have been selected from the recording period (May 27th - June 24th 2009). The magnitude (Ml) of the recorded aftershocks reached a maximum of 4.5, the epicenter distance (from the reference station) ranged from 0.5 km to 30 km (Fig. 6). Among these recordings, we selected the ones that were sufficiently long and that presented a low frequency content to allow a windowing of about 30 s which is mandatory for the SSR to be relevant down to a frequency of 0.3 Hz. Because of the short source-to-site distance, it was impossible to separate the P and S arrivals and both are thus included in the analysis. The reference station considered here is located on limestone in Poggio di Roio, about 2.5 km south of L'Aquila city center.

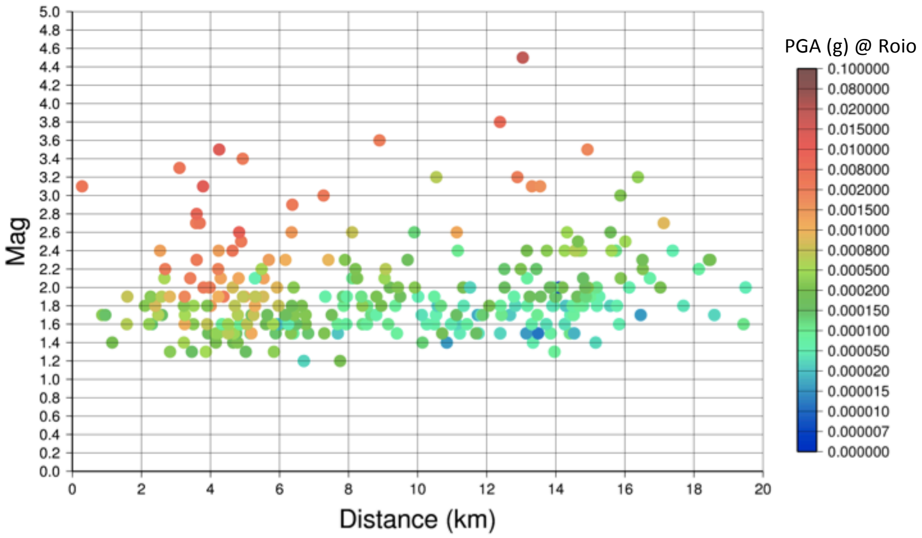

Figure 6. Events recorded during the L'Aquila historical center monitoring.

The computed SSR are in good agreement with the HVNSR. For example, both of the curves at the FAQ1 station located at Piazza San Marco in the heart of L'Aquila exhibit a first peak at about 0.5 Hz and a lower amplitude peak around 5 Hz (Fig. 7). At this station, the soil seems to amplify by a factor of 10 the signal at 0.5 Hz regarding the recordings at the reference station (Roio di Poggio). At station FAQ6, installed in the front garden of L'Aquila's castel, these peaks are also recovered on both SSR and HVNSR curves, but the amplitude of the higher frequency peak is larger than the 0.5 Hz one. In this case, the signal at 5 Hz is, on average, 11 times larger than the one recorded at the reference station.

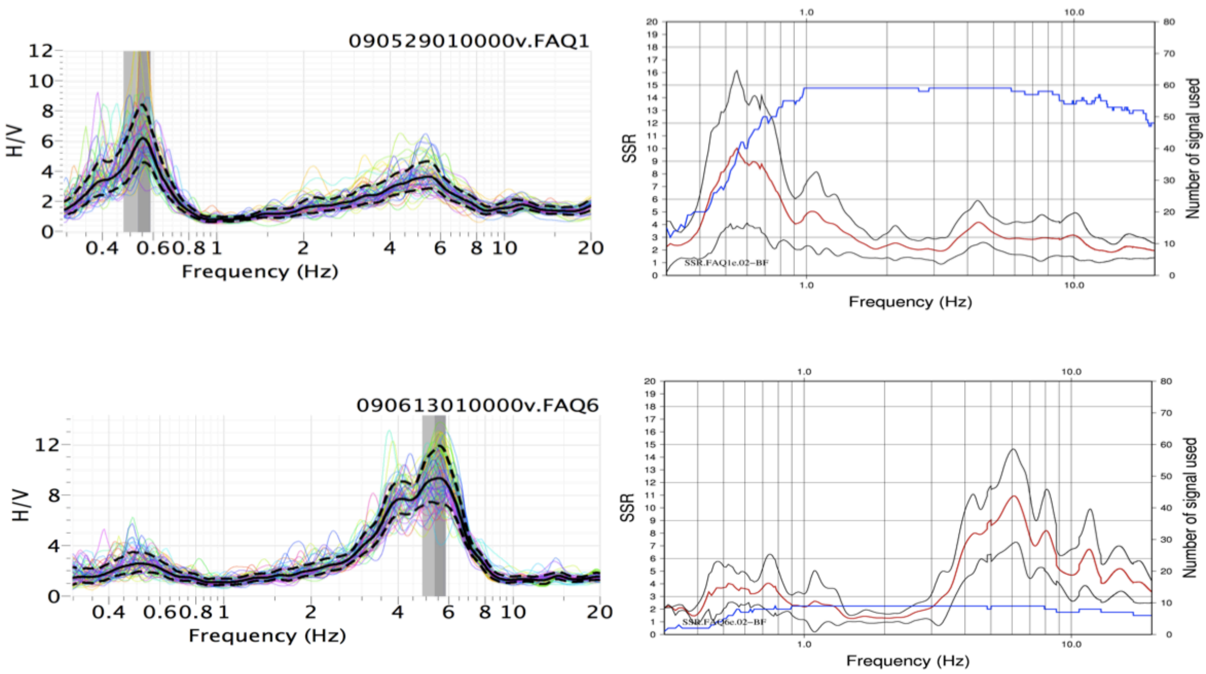

Figure 7. Comparison between SSR (NS component, right) and HVNSR (left) at stations FAQ1 (top) and FAQ6 (bottom). HVNSR: mean ratio in black solid line, standard deviation in dash line. The colored lines refer to the ratio from single windows. SSR: mean ratio in red, standard deviation in black and number of signal used in blue. For each frequency, the recordings for which the signal-to-noise ratio is higher than 3 are only considered.

We observe a larger standard deviation for the SSR than the HVNSR. Indeed, the level of amplification estimated by the SSR technique at station FAQ1 varies between 4 and 16 at 0.55 Hz. At the same frequency, the HVNSR varies only from 5 to 8. This variability could be due to the distribution of aftershocks regarding the array aperture, the difference of the source-to-station travel paths and the complexity of the geology in the area.

The amplification at the fundamental resonance frequency seems to be quite important in the historical center of L'Aquila. In this area, the maximum signal amplification regarding the station in Roio di Poggio is, on average, equal to 10. This high level of amplification is not only seen on the horizontal component of the ground motion but also on the vertical one (Fig. 8). However, the frequency associated with the maximum amplification on the vertical component is slightly higher. On this component, it varies between 0.9 Hz and 1.2 Hz.

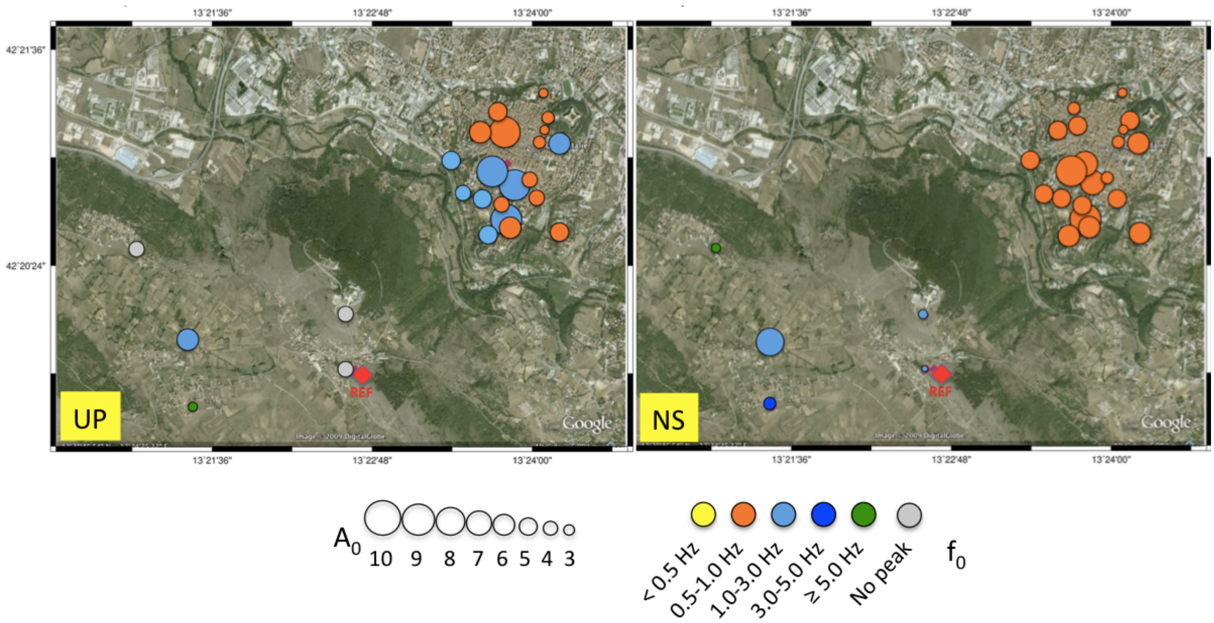

Figure 8. Resonance frequency estimated from the SSR at L'Aquila and Roio areas. Vertical component (Left) and NS horizontal component (Right) are shown. The reference station considered is the one located in Poggio di Roio (red diamond).

Almost everywhere in the city, two peaks that can be interpreted as the resonance frequencies of a shallow quaternary layer and a thicker deposit characterize the SSR. This is particularly true close to the castle, where the second peak is much higher than the first one. The low resonance frequency obtained here confirms the results obtained by De Luca et al. (2005). These authors also correlate the resonance frequency with the presence of a deep sedimentary basin filled with Quaternary deposits that possibly reach a thickness of 200 m. These sediments are buried by a thick layer of calcareous breccia with different degree of cementation. The thickness of this shallow layer varies between 20 and 50 m. The S-wave velocities in the Quaternary deposit have been estimated to be around 500 m/s to 650 m/s, whereas in the breccia the Vs should be of about 900 m/s (De Luca et al., 2005; Blumetti et al., 2002).

4. CONCLUSION

The April 6th, 2009 earthquake that struck the Abruzzo region caused hundreds of causalities and mostly affected L'Aquila city and the village of the upper and middle Aterno valley. Many buildings collapsed and the ancient masonry suffered particularly. Local site effects are one of the keys that can explain the damage distribution, along with the distance to the source and the vulnerability of the construction. The intervention of the international research group has allowed better constraint of the ground motion that affected the area and its discrepancy in the valley, by collecting and analysing the recordings of low-to-moderate magnitude events in a large number of sites.

HVNSR and SSR are very much consistent. The first results obtained confirm the presence of large amplification effects both in the L'Aquila historical center and in the suburban areas. The soil in the historical center of L'Aquila exhibits a rather low resonance frequency at about 0.5 Hz. That is consistent with what previous studies suggest about the geological setting of the valley (De Lucca et al., 2005). A clear local effect is also detected there on the vertical component but a at slightly higher frequency (0.9 Hz-1.2 Hz). In the suburban quarter we found large amplifications at frequencies ranging from 2 Hz to 5 Hz.

The results presented in this paper are derived from a preliminary study. The large amount of data collected during the seismological monitoring during the 2009 earthquake sequence will allow us to perform more detailed analysis in order to enhance our comprehension of the phenomena and in particular the role of the peak ground acceleration, the source-to-site azimuth or the epicentral distance in the observed ground motion amplification in L'Aquila.

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