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Evidence of Low-Frequency Amplification in the City of L'Aquila, Central Italy, through a Multidisciplinary Approach Including Strong- and Weak-Motion Data, Ambient Noise, and Numerical Modeling

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Abstract Recent accelerometric recordings of earthquakes with moderate and intermediate magnitude ($4.0 < M_L < 5.9$), at both local and regional distances, show a significant ground-motion amplification effect at low frequencies (0.6 Hz) in the city of L'Aquila (central Italy). The effect involves very long durations characterized by low frequencies in the coda.

Starting from these observations, a series of supplementary investigations was performed in the urban area of L'Aquila by collecting and analyzing both weak-motion data from earthquakes with magnitudes ranging from 2.2 to 4.9 at distances from 20 to 105 km and ambient noise data.

All the collected weak-motion data share the same characteristics as the strong-motion records and give a better image of the amplification effect in the city. In order to interpret observations in terms of the local geology, we performed 2D numerical modeling of the sedimentary basin underlying the city of L'Aquila using both finite elements and boundary elements based on a geological section derived from gravity measurements.

This analysis indicates that the ground-motion amplification in the city of L'Aquila is related to the presence of a sedimentary basin, filled by lacustrine sediments, with a maximum depth of about 250 m.

The combined approach to data collection and analysis used here gives useful information for risk assessment in the city of L'Aquila and can be recommended for many other urban areas that share similar characteristics.

Introduction

L'Aquila is one of the most important and populated cities in central Italy, with about 70,000 inhabitants. The city is located in the central part of the Apennine chain, a region characterized by normal fault earthquakes (Westaway and Smith, 1989; De Luca *et al.*, 2000) that have in the past reached macroseismic intensities up to XI on the Mercalli-Cancani-Sieberg scale (MCS), corresponding to an M_s close to 7 and causing damage [Working Group Catalogo Parametrico, dei Terremoti Italiani (CPTI), 1999]. This region exhibits seismic characteristics similar to those observed in the southernmost part of the Apennine Mountains, where the major earthquakes are related to normal faulting systems striking along the direction of the mountain chain (De Natale *et al.*, 1988; Bernard and Zollo, 1989; Westaway and Smith, 1989). The seismicity rate is lower than that observed in the adjacent regions northwest of L'Aquila (Umbria and Marche), but with a more frequent occurrence of high-magnitude events (Galadini *et al.*, 1999; Cattaneo *et al.*, 2000; Deschamps *et al.*, 2000).

Structural and recent paleoseismological studies (Bachetti *et al.*, 1990; Lavecchia *et al.*, 1994; Galadini and Galli, 2000) indicate the presence of major active fault systems at distances of about 10 to 100 km from L'Aquila, which can produce highly damaging events (Fig. 1). This observation is also supported by historical seismicity studies (Working Group CPTI, 1999), which show that the city suffered substantial damage (IX–X MCS) during at least three events in the last 1000 years (1349, 1461, and 1703). In addition, several events were felt at a lower intensity level (VII–VIII MCS). Source regions for these events are at both local and regional distances (Lavecchia *et al.*, 1994; Galadini and Galli, 2000).

Owing to the importance of the area from a seismotectonic point of view, the Servizio Sismico Nazionale (SSN) started a program of microseismic monitoring at a regional scale by installing a digital seismic network in the early 1990s, (De Luca *et al.*, 2000). The instrumental recordings show diffuse low-magnitude seismicity with the occurrence

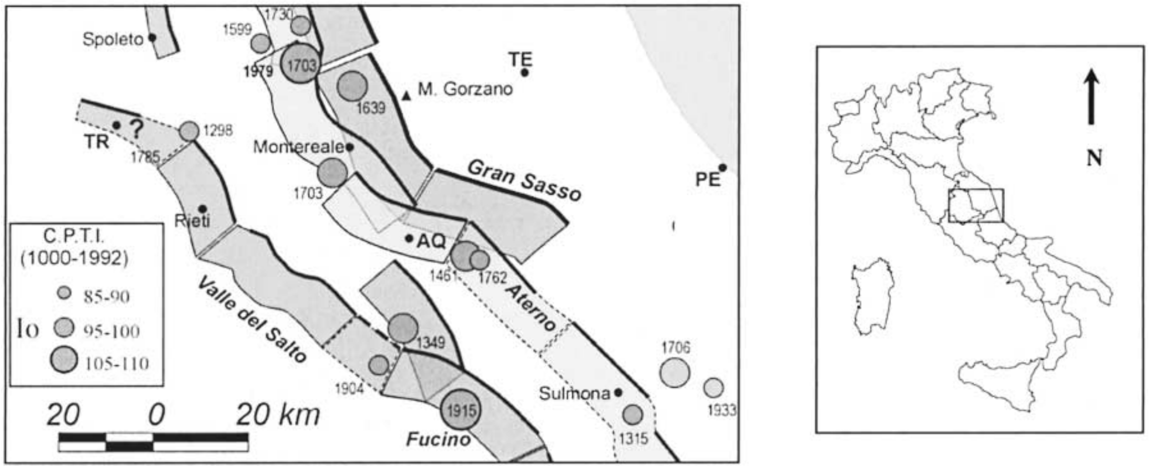

Figure 1. Sketch of major active normal fault systems in central Italy, black solid lines, (from Lavecchia *et al.*, 1999, modified). The box in the Italy map is the area represented in the left part of the figure. Circles show historical earthquakes. Data are taken from Working Group CPTI (Catalogo Parametrico dei Terremoti Italiani) (1999). The question mark refers to the uncertain 1785 earthquake. The location of L'Aquila (AQ) and major cities Terni (TR), Teramo (TE), and Pescara (PE) are represented by black dots. Io is MCS epicentral intensity.

of at least three earthquake sequences located a few kilometers north-northwest of the city and probably associated with known seismogenetic structures (De Luca *et al.*, 1998; De Luca *et al.*, 2000; Boncio *et al.*, 2004).

Hazard studies confirm that the area of L'Aquila is exposed to high risk (Boschi *et al.*, 1995; Bongiovanni *et al.*, 1996; Romeo and Pugliese, 2000). In particular Romeo and Pugliese (2000) find a high probability of a peak acceleration exceeding 0.25g in a 50-year period using a Poissonian approach. The probability of an earthquake with magnitude $M_S > 6.3$ in the next 30 years increases to 23.6% in L'Aquila area using a renewal approach (Romeo and Pugliese, 2000). The area is characterized by the presence of an important sedimentary basin, where a strong-motion microarray was installed beginning in 1994 in order to evaluate local site amplification. The array AQPK is composed of three strong-motion stations, located in the center of L'Aquila, and it includes one station installed in an underground tunnel (Fig. 2) (Bongiovanni *et al.*, 1996).

We studied the local site amplification effect due to the sedimentary basin, whose characteristics are similar to those in many other areas of the Appennine Mountains. To achieve our purpose, we analyzed with standard spectral approaches data collected by the accelerometer array during local and regional events, along with weak-motion and microtremor data recorded by temporary three-component digital short-period stations. We also performed a 2D numerical simulation of the sedimentary basin seismic response using previously published results of a gravity survey to constrain the basin geometry. The observed response was compared with the simulation for verification of the basin model. This approach allowed us to obtain detailed information on the seismic amplification effect, of interest to engineering seismologists.

Geological Setting of L'Aquila

The city of L'Aquila (founded in 1245) is located in a tectonic basin bounded to the north by a northwest–southeast-trending active normal fault (Blumetti, 1995; Bagnaia *et al.*, 1996).

Downtown L'Aquila is set on a fluvial terrace, which forms the left bank of the Aterno River (Fig. 3). The elevation of the terrace reaches 900 m a.s.l. (above mean sea level) in the northeastern part of the city and slopes down to 675 m a.s.l. in the southwest direction. The terrace ends at the Aterno River which flows 50 m below. The alluvial deposits that constitute the terrace are lower Quaternary in age, and are composed of breccias with limestone boulders and clasts in a marly matrix. Clast dimensions can range from centimeters to meters. This kind of deposit is common in the Abruzzo region and may be related to catastrophic alluvial events associated with landslides (Blumetti, 1995). The deposits were studied by Demageout (1965), who named them "megabrecce." The megabrecce represents a well-defined geological unit with flat top and bottom surfaces and a thickness of some tens of meters, lying on lacustrine sediments composed mainly of silty and sandy layers and minor gravel beds.

The thickness of the lacustrine deposits was investigated by a geological and morphological analysis along with a gravity survey (Blumetti *et al.*, 2002). The authors drew several cross sections across the L'Aquila basin and the Aterno River valley in both the city center and in the adjacent areas.

The lacustrine sediments reach their maximum thickness (around 250 m) in the center of L'Aquila. In contrast, in the Aterno River valley, north of L'Aquila, the thickness of the sediments is never greater than 100 m.

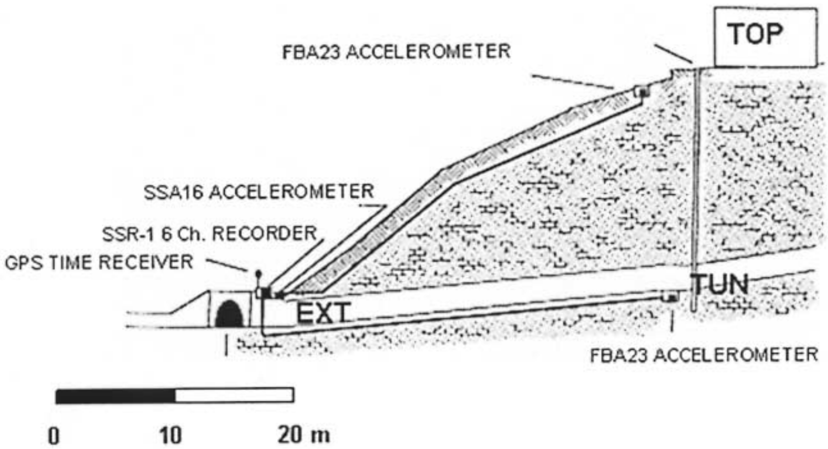

Figure 2. AQPK strong-motion array. Instrument locations (TOP, TUN, EXT) are shown. The horizontal and vertical scales are the same.

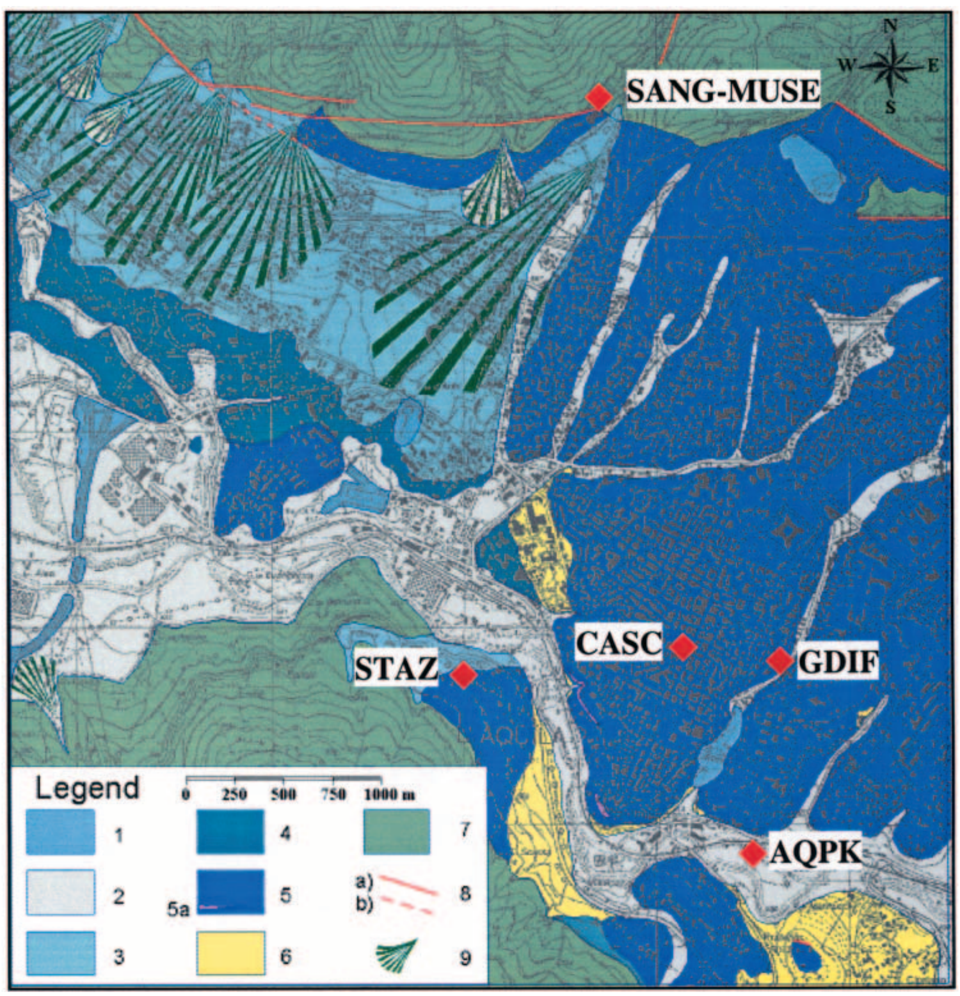

Figure 3. Geological map of the urban area of L'Aquila from Blumetti *et al.* (2002), modified. Red rhombuses represent the locations of the seismic stations used in this work. Geological units are as follows: (1) anthropic deposits; (2) Holocene alluvial deposits; (3) alluvial fan and debris deposits; (4) terraced alluvial deposits; (5) megabrecce; (5a) silty levels; (6) lacustrine deposits; (7) limestone bedrock; (8) active fault: (a) outcrop and (b) inferred; (9) alluvial fan.

The new industrial area of L'Aquila and recent housing developments are built directly on lacustrine sediments.

Methods

Site amplification studies are often based on empirical approaches well known in the literature. Most of these techniques are based on spectral ratios of the horizontal component of ground motion collected at soil and rock sites or between the horizontal and vertical components of ground motion at a single recording site. The first approach, the S/R method, requires a reference site; the second, the H/V method, can be applied at a single station (Borcherdt, 1970; Tucker and King, 1984; Aki, 1988; Lermo and Chavez Garcia, 1993; Field and Jacob, 1995).

The choice of a reference site is not a trivial issue but can be eliminated by using H/V techniques based on a single-station approach. The H/V technique was developed for seismic noise by Nakamura (1989) and relies on purely empirical observations, although it has been partially justified by theoretical considerations (Field *et al.*, 1992; Lachet and Bard, 1995). Despite the lack of theoretical background, Nakamura's technique is at present one of the most often used methods to derive a relationship between the thickness of the soft layer and the frequency peak of the amplification function (Yamanaka *et al.*, 1994; Ibs-von Seht and Wohlenberg, 1999). Some researchers (Lermo and Chavez Garcia, 1993; Field and Jacob, 1995; Huang and Teng, 1999) have recently applied this technique to direct S waves rather than to ambient noise and have obtained some good results. To date, the most convincing explanation of the H/V technique is provided by Konno and Ohamachi (1998). Additional discussion about spectral techniques for site effect evaluation is provided by Bard (1999) and Delgado *et al.* (2000).

In our analysis, we applied the H/V technique using both *S* waves and coda waves for earthquake data recorded by the strong-motion array. This single-station H/V method was necessary because none of the utilized events were recorded at a rock site close to the array.

The weak-motion earthquake data recorded by permanent and temporary short-period instruments were processed using the S/R method on S waves. This was possible because the low-magnitude events were recorded without saturation by one station located on a rock site very close to the center of L'Aquila.

Microtremor data were analyzed with the classical Nakamura method because the extended area of investigation precludes definition of a reference site. A detailed description of the data analysis is reported in the next section.

Data Collection and Analysis

Strong-Motion Data

The starting point of our observations was the M_L 4.0 earthquake that occurred on 20 October 1996 close to Montereale village about 20 km northwest of L'Aquila (Fig. 1) (Boncio *et al.*, 2004). This event triggered the AQPK array (Figs. 2 and 3) composed of three strong-motion stations, equipped with Kinematrics FBA 23 sensors connected to 12–16 bit digital recorders and sampled at 200 Hz.

The array was originally designed to investigate the behavior of a 40- to 50-m-thick gravel layer, which represents the principal geological unit cropping out in the city center, because the gravel was thought to be the cause of some local amplification effects. The three AQPK stations were installed at locations with different geological conditions. The first (TOP) is deployed on the top of the gravel layer, the second (EXT) at its base, and the third (TUN) in a tunnel carved in the gravel layer. The gravel layer lies on thick lacustrine sediments. Because the stations are close together, the thickness of the lacustrine layer can be considered constant. The bedrock is limestone at a depth greater than 200 m. Moving away from the TOP station, the morphology flattens, so any topographic effect can be due only to the scarp shown in Figure 2.

The time histories of the Montereale event are shown in Figure 4a and b, along with their Fourier spectra. A visual inspection of the record shows a clear long-duration low-frequency signal (0.5–1.5 Hz) in the coda, common to all the recording stations, which becomes the predominant part of the ground motion.

The spectra of the recorded data are shown in Figure 4b. They were evaluated on a 14 sec long-time cosine-tapered window including *S* waves and part of the coda. The three spectra show an important peak in the low-frequency range with the same amplitude at all the recording sites. Station TOP is enriched in high frequencies owing to the presence of the gravel layer or to some topographic effect, while station TUN presents a quick decay at high frequency related to its underground location. Station EXT shows a spectral shape with a more balanced contribution between high and low frequencies. Some of the described spectral characteristics are quite interesting, but we focused our attention on the common feature represented by the low-frequency peak.

Because of the low magnitude of the event, which theoretically requires a corner frequency above 1 Hz, the low-frequency content of the signals cannot be explained in terms of source and path effects. The peak can be reasonably associated with the presence of some site effect independent of the gravel layer and probably related to the behavior of the underlying lacustrine clays. Also, the unusual duration of the records appears to be compatible with the presence of local site effects due to the resonance of the sedimentary basin.

After the 1996 event, the AQPK array recorded four more events of the 1997 Umbria-Marche sequence (26 September, 6 October, and 14 October) with M_W ranging from 5.6 to 5.9 and distances between 80 and 100 km (Zollo *et al.*, 1999; Capuano *et al.*, 2000; Morelli *et al.*, 2000). Those data are part of the strong-motion data set used in this study.

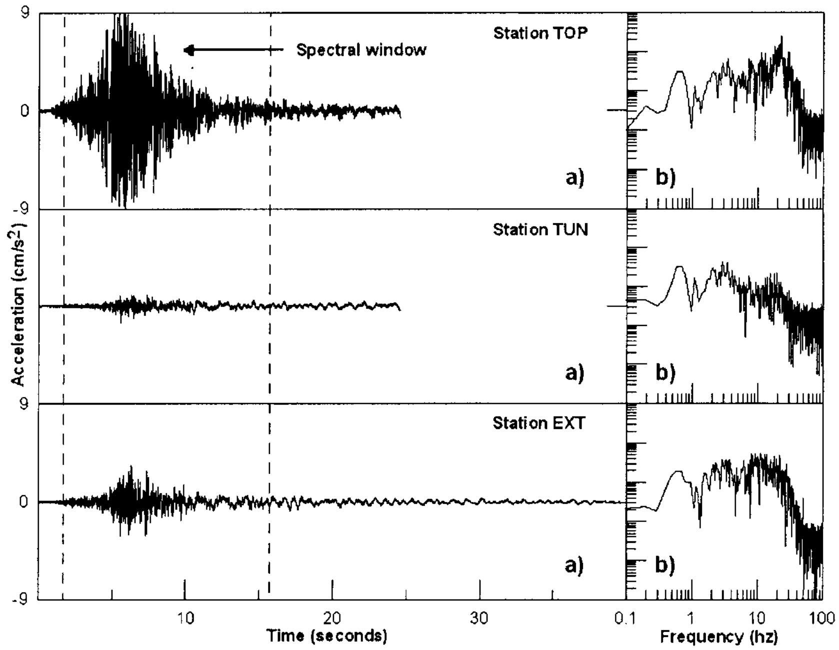

Figure 4. AQPK array time histories (4a) for the east–west component recorded during the Montereale (20 October 1996) M_L 4.0 event. Fourier spectra calculated on the marked window are also shown (4b).

We applied H/V ratios to investigate the possible presence of amplification factors at the AQPK site because of the lack of a close reference rock station for comparison with the AQPK data. The data were cosine-windowed on one 20-sec section of the record that included the strong-motion phase and was dominated by direct *S* waves. The records related to the Umbria-Marche sequence show a longer duration, and we selected a 40-sec section of signals following the strong-motion part and dominated by the coda of the signals.

The results of the analysis are summarized in Figure 5, which shows the average H/V ratios both for *S* waves and coda windows. The H/V spectral ratio shows an amplification factor at frequencies lower than 1 Hz, with a peak centered at 0.5–0.6 Hz. Peaked frequency is more evident in the coda of the signals and is quite stable for the entire record used and for both the horizontal components. Also the amplitudes, which reach values of 6–7 for the coda data are quite stable for all the analyzed data.

The stability of the results in the coda of the signals suggests the presence of local resonances in the sedimentary basin.

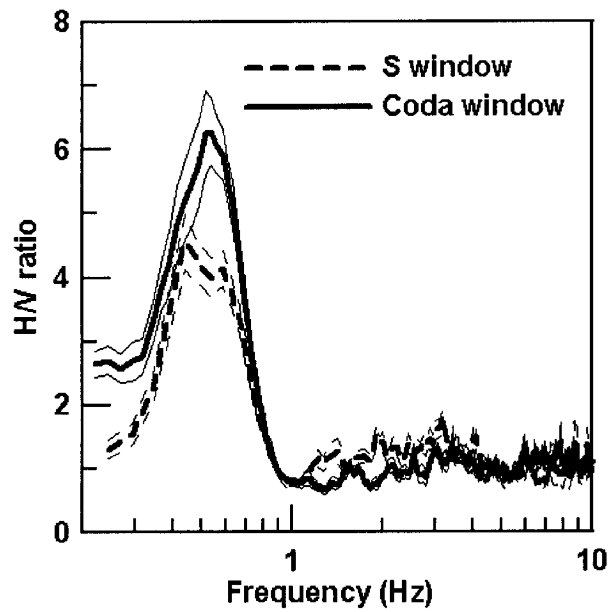

Figure 5. H/V ratio mean values with standard error ($\pm 1\sigma$) evaluated using *S* and coda waves from the AQPK underground station. The average of five events, including the Montereale earthquake, is shown. This last event was not used in the coda-wave average because of the short duration of the record.

Weak-Motion Data

To obtain a greater number of records at the AQPK site, to investigate one other location in the town, and to test the dependence of amplification factors from the ground-motion level, we installed two digital three-component seismic stations, which recorded data related to local and regional events of low magnitude. The first station (AQPK) was deployed close to EXT at the base of the gravel layer (Fig. 3). The second station (CASC) was installed in the northern part of the older town, on gravel overlying lacustrine sediments (Fig. 3).

These stations were equipped with a Lennartz Mars88-FD data logger, with a 20-bit A/D converter connected to a Mark L-4C-3D (1-Hz) seismometer with the sampling rate set to 125 Hz.

We also considered data from a station belonging to the regional digital seismic network operated with the same kind of instruments and installed in the Monastery of San Giuliano (SANG), about 3 km away from AQPK (Fig. 3) on outcropping limestone (De Luca *et al.*, 2000).

During more than 1 year of operation (from January 1997 to February 1998), we recorded 100 events with local magnitude ranging from 2.2 to 4.9. These events were located using the Abruzzo network data and the Hypo71 algorithm (Lee and Valdes, 1985). The epicentral distribution was spread out in the regional area at different azimuths with distances ranging from 2 to 105 km. Figure 6 shows an example of one horizontal component recorded simultaneously at SANG, CASC, and AQPK where the variability in duration and low-frequency content is quite clear.

Because of the availability of a reference station (SANG), we decided to analyze the weak-motion data using the conventional reference site technique, to compare the results with those obtained with the AQPK strong-motion data and to infer information about another site located in L'Aquila's historical center.

The reference station technique assumes that source and path effects can be considered the same at both reference and site stations. This condition can be met if the earthquake–station distance is much bigger than the rock site–sediment site separation. To fulfill this condition, we decided to use only data with station–epicenter distances greater than about 20 km.

Another concern was the signal-to-noise ratio of the recorded data. This is particularly important with low frequencies that can be characterized by low energy for small-sized events. Following up on this idea, we performed a signal-to-noise analysis cutting, with a cosine window, a 15-sec section of preevent noise, and a 15-sec window starting 1 sec before the *S* wave arrival time. The Fourier spectra were evaluated for each event on both noise and *S*-wave windows, and only the data presenting a good signal-to-noise ratio in the low-frequency range were selected for the succeeding computations.

As a result of the analysis performed, we excluded 48 events, reducing the weak-motion data set to 52 events recorded simultaneously at the three stations.

The weak-motion data set was still dominated by events related to the Umbria-Marche sequence with regard to the source–receiver azimuth. Some additional data with different azimuths were available after the selection, which allowed us to partially smooth out the azimuth dependence of the amplification factors and to obtain average response curves.

The amplification factors were evaluated for both horizontal components on the 20-sec *S*-wave window for both AQPK and CASC using SANG as the reference site. The computed spectral ratios were smoothed and averaged to obtain the average amplification function.

The results for AQPK showed a 0.5–0.6 Hz peak on both horizontal components in good agreement with H/V results for strong-motion records.

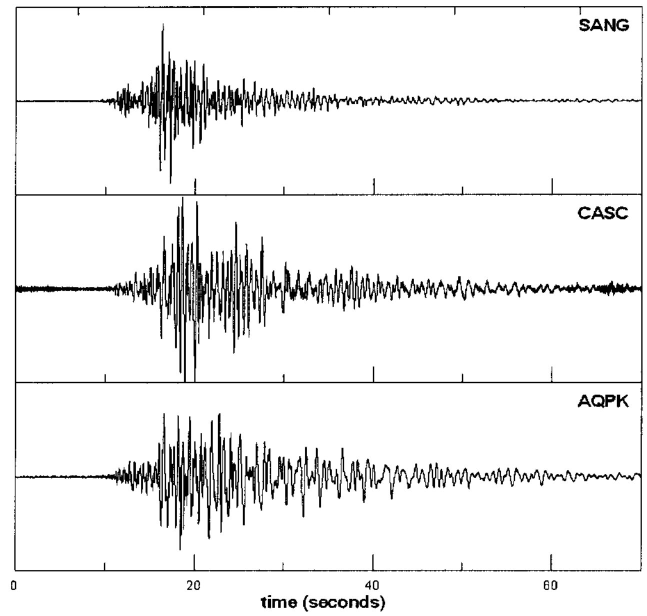

Figure 6. Plot of the east–west components of the 7 May 1997 (M_L 4.2, distance 50 km) event recorded simultaneously at the CASC, AQPK, and SANG stations. All the records are plotted at the same scale.

Spectral ratios for AQPK also showed an extension of the amplification band just above 1 Hz, which was not present in the strong-motion data. This observation may be related to the fact that the station was located outside of the AQPK tunnel, and some effect due to the gravel layer may be present.

For CASC, a low frequency peak, with a lower amplification value, is present on one of the horizontal components, while on the other component, the amplification band is broader and centered at higher frequencies, about 1 Hz, and with very low absolute values (Fig. 7).

Microtremor Data

The idea to record microtremor data was suggested by the persistence of the amplification factor at low frequency and its apparent independence of the amplitude of ground motion in the analyzed deformation range. The investigated area is favorable for applying Nakamura's method due to its capability to detect the fundamental frequencies of sedimentary layers (Bard, 1999). We decided to use this technique to enlarge the investigation area to include some sites in the historical center of L'Aquila to better describe the spatial extent of the low-frequency amplification factor. We installed five digital seismic stations (Fig. 3) equipped with a Lennartz Marslite data logger (20-bit A/D converter, 125 samples/sec) connected to three-component velocity transducers (Lennartz LE3D-5) with the frequency response extended down to 0.2 Hz.

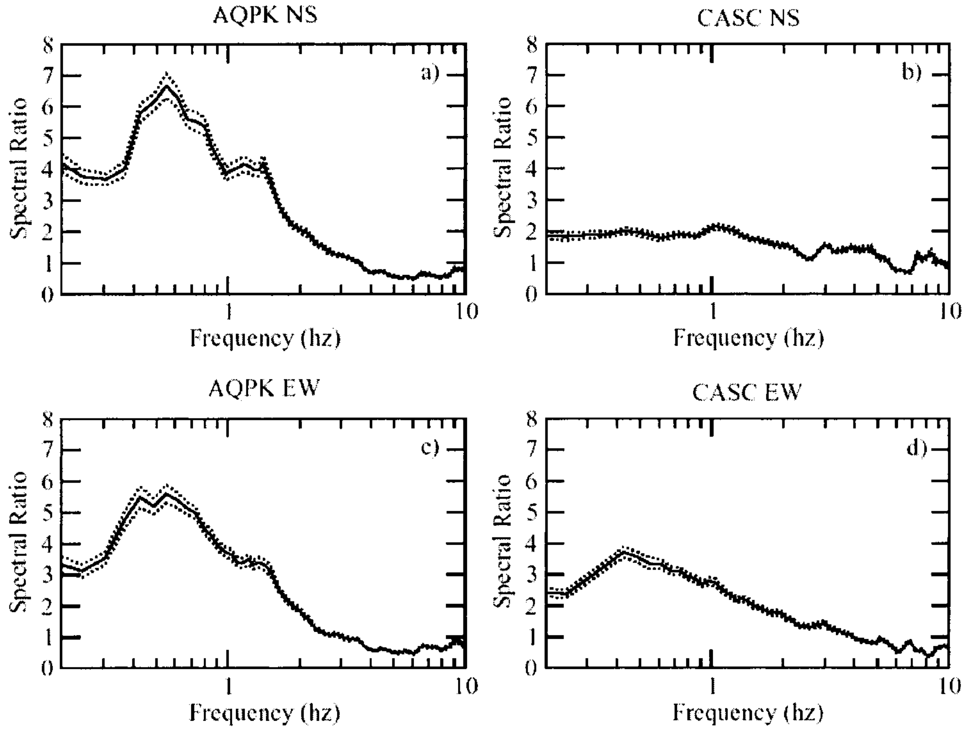

Figure 7. S/R ratios evaluated using 52 selected events, from a data set of 100, recorded simultaneously at the SANG, CASC, and AQPK stations, with their errors ($\pm 1\sigma$) using SANG as the reference site. The figure shows spectral ratios of the north–south component for AQPK (a) and CASC (b), and spectral ratios of the east–west component for AQPK (c) and CASC (d).

The first station was installed on outcropping limestone at the Monastery of San Giuliano (MUSE) close (less than 100 m) to the SANG station of the Abruzzo seismic network (De Luca *et al.*, 2000). The second station was installed at the site of the AQPK underground strong-motion station, and the third station was close to the railroad station (STAZ), outside of the city historical center and closer to the Aterno River and to the edge of the sedimentary basin (Fig. 3). The other two stations (GDIF and CASC) were installed in the northern part of the older city at the positions shown in Figure 3.

All the stations were programmed for continuous recording on a time window at least 24 hr long. All the collected data were cut into 60-sec long-time windows and processed with a fast Fourier transform (FFT) algorithm to evaluate Fourier spectra. The results obtained were smoothed on a 0.2-Hz halfwidth frequency band. The H/V spectral ratios are shown in Figure 8.

Microtremor data also showed the presence of the amplification factor at 0.5–0.6 Hz at the AQPK site for both horizontal components; the same peak was still present, even if with low amplitude, at GDIF and CASC, which were located in the historical center of the city. A different behavior was shown by the STAZ site, with a lowering of the amplitude and a shift toward higher frequencies. Finally, MUSE did not show any amplification at low frequencies, consistent with the geological characteristics of the site (De Luca *et al.*, 1998).

As a result of our data analysis, the low-frequency (0.5–0.6 Hz) amplification factor was clear at the AQPK site and independent of the amplitude of the input ground motion. This peak was very stable and seemed to be present at other sites located in the city center. Approaching the western edge of the sedimentary basin, it was possible to observe a modification of the amplification factors, both in amplitude and in frequency. In addition, we also proved that the SANG-MUSE site can be considered a good reference site since it does not show any particular amplification factors.

As a final remark, we observed an important amplification factor at low frequency with all data sets and methods used. This feature can be associated with the presence of the sedimentary basin filled with lacustrine sediments. The presence of the outcropping gravel layer did not contribute to the amplification function because it could be considered as a rigid body with high shear-wave velocity.

Numerical Modeling

The behavior of the sedimentary basin was evaluated using a simple 2D scheme in order to model the low-frequency amplification derived from experimental data. The

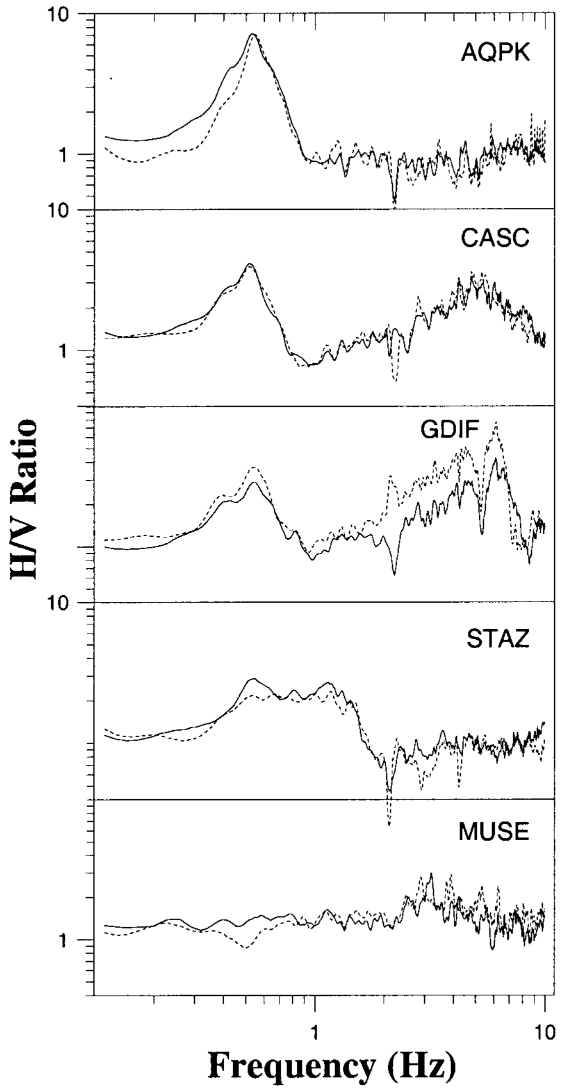

Figure 8. Microtremor H/V ratios at the AQPK, CASC, GDIF, STAZ, and MUSE sites (see figure for their locations). The continuous line refers to north–south components and the dashed line to east–west components.

analyses were performed through the computer codes BESOIL (Sanò, 1996) and QUAD4M (Hudson *et al.*, 1994).

BESOIL uses an indirect boundary formulation for dynamic elasticity. It is based upon the integral representation of the diffracted elastic waves in terms of single-layer boundary sources (Sanchez-Sesma and Campillo, 1991; Sanchez-Sesma *et al.*, 1993). This approach, known as the indirect boundary element method (BEM), provides information on the physics of diffraction problems because diffracted waves are constructed at the boundaries from which they are radiated. The 2D space is divided into zones, in which the mechanical properties are constant.

Consider the elastic material in a homogeneous region V with boundary S. The displacement field in a generic internal point r can be described, in the absence of body forces, with a boundary integral:

$$u_i(r) = \int_S \phi_j(r') \times G_{ij}(r,r')dS' \qquad (1)$$

where $u_i(r)$ is the ith component of displacement at r, $G_{ij}(r,r')$ is the Green's tensor, that is, the displacement in the direction i at point r due to the unit force applied in the direction j at point r', and $\phi_j(r')$ is the force density on the boundary in The j direction. The closed-form solution of The Green' function has been derived for 2D elastodynamic problems of the whole space (Kummer *et al.*, 1987). The above equation shows that the displacement of any internal point can be determined as the sum of the effects of forces applied at the boundaries. The equation stems from the Somigliana identity, which is the basis of the direct approach of the BEM. Kupradze (1963) showed that the displacement field is continuous across boundary S, if ϕ_j is continuous along S. Stresses and tractions can be calculated by direct application of Hooke's law except at the boundary singularities, that is, when $r \rightarrow r'$ on the boundary. In this situation, the Green's function, G_{ij}, has a logarithm-type integrable singularity, but its derivative can be computed only if the singularity is extracted (Kupradze, 1963). The integral can be calculated, by a limiting process, based on equilibrium considerations around the singularity, in the following form:

$$t_i = C\phi_i(r) + \int_S \phi_j(r') \times T_{ij}(r,r') \times dS' \qquad (2)$$

where t_i is the ith component of traction at the boundary and C is equal to zero outside the boundary and equal to $\pm$ 0.5 for a smooth boundary. The signs + or − are valid respectively for the interior and exterior domain. $T_{ij}(r,r')$ is the traction Green's function and represents the traction in direction i at point r on the boundary due to the application of a unit force in the direction j applied at r'. The above equations are the basic formulations for solving the problem of wave propagation under the incidence of elastic waves. From the boundary conditions on the free field and on each boundary between the zones, a system of integral equations for boundary sources is obtained. Subsequently a discretization scheme based upon the numerical and analytical integration of exact Green's functions for displacements and traction is used (Sanò, 1996; Pergalani *et al.*, 2002). The method is suitable for the analysis of an irregular ground, since it can easily formulate an obliquely incident wave and outgoing scattering waves.

QUAD4M is based on the finite element method and performs an equivalent time-domain linear simulation. It represents the evolution of the QUAD4 code (Idriss *et al.*, 1973) modified to take into account a transmitting lower boundary in order to reduce amplification overestimation due to the presence of a rigid boundary. The problem is approached by a single-step time-domain integration with constant parameters. The rigidity and damping matrices are modified at the end of every iteration in order to take into account nonlinear soil behavior as used in SHAKE code (Schnabel *et al.*, 1972).

However, since only amplifications at low intensity were considered, only a linear analysis was performed and no iterations were necessary. Material properties regarding the strain dependency of G (shear modulus) and damping did not affect the results.

One important parameter to take into account when using finite element models is the grid dimension, which is related to the resolved frequency interval. In our application, we were interested in modeling the low-frequency behavior, namely the 0.6-Hz amplification peak. In order to define the grid-point spacing, we assumed a minimum V_S velocity of about 300–400 m/sec and applied the formula (Lanzo and Silvestri, 1999):

$$h = \frac{V_S}{6 f_{\max}} \tag{3}$$

where h is the thickness of the grid element and $f_{\max}$ is the maximum resolved frequency. We set h to 25 m in order to get information up to 2 Hz.

The 2D profile used as a base for our modeling was derived from the results recently presented by Blumetti *et al.* (2002), who combined a detailed geological survey of the urban area of L'Aquila with a morphotectonic analysis and gravity prospecting aimed "at defining the geometry of the contact between the bedrock and the Quaternary deposits underlying the city." The geological survey was performed at a 1:5000 scale and was able to define the extent of the Quaternary deposits. All the available subsurface data were used even though they mostly related only to a few tens of meters. Gravity prospecting was performed at 132 measuring points distributed in the city center and in nearby areas (Blumetti *et al.*, 2002). The residual gravity anomalies show a low-gravity area extending north–northwest, with a steeper gradient toward the western edge of the Aterno River valley (Fig. 9a).

The geological section we used for numerical modeling is transverse both to the Aterno River valley and to the negative gravity anomaly. It represents a simplified version of the section proposed by Blumetti *et al.* (2002).

The geometry of the profile shows an asymmetric basin with a steep western edge, probably related to a tectonic discontinuity, and a more gently sloping eastern edge; the maximum depth of the basin is assumed to be 250 m (Fig. 9b). The outcropping units are represented by megabrecce except in the Aterno River valley, which is filled with recent fluvial sediments.

Unfortunately, subsurface geotechnical investigations are not available at the present. One possible reason for this lack of information is the presence of the megabrecce layer, which covers the Quaternary deposits and presents good geotechnical characteristics as a foundation material. The geotechnical drillings available in the area do not reach the lacustrine layer below the outcropping megabrecce. Moreover, geotechnical investigations are difficult and are rarely performed in the ancient city center owing to the very high density of old buildings. To overcome this problem, we derived a shear-wave velocity distribution starting from two SASW surveys (Stokoe *et al.*, 1989), also conducted by SSN. The measurements were performed in the center of the city and on outcropping clays south of L'Aquila as part of work for a dissertation thesis (Pasqualetti, 2001). This work determined both *S*-wave velocities and thickness for the megabrecce and for the uppermost (40–50 m) part of the lacustrine sediments (Table 1 and Fig. 9b). The velocity for the lowermost part of the clays was estimated from literature data.

The input signal for the modeling was a simple Richer wavelet centered at a frequency of 1 Hz. This simple waveform allows us to check for the presence of artifacts in the output signals caused by numerical instabilities. Another advantage in using this input signal is its narrow band, which avoids introducing into the model frequencies higher than those allowed by the grid spacing.

In Figure 9b, we show the cross section used in the numerical modeling along with the amplification functions obtained with QUAD4M code as spectral ratios between synthetic signals evaluated in nine different locations of the section and the synthetic signal on outcropping rock.

It is clear that a low-frequency amplification factor arises in the deepest part of the basin, whereas no amplification is found near the edges. The frequency of the observed amplification matches the 1D modeling results using vertically propagating *SH* waves.

The AQPK station was near the S05 receiver (Fig. 9b) at a distance of about 1100 m from the western edge of the basin. The GDIF station was farther east, at a distance of around 1850 m, near the S07 receiver. The other two stations (STAZ and CASC) were outside the area of the profile and could not be directly compared with the 2D model.

Figure 10a and 10b compare QUAD4M and BESOIL results, and confirm that both codes are able to predict the low-frequency amplification peak in the deepest part of the basin. BESOIL solutions are more complex because the code allows higher frequencies. The high-frequency behavior found using BESOIL code cannot be considered physically significant because the model used is not realistic at a small scale. The QUAD4M results seem to be less sensitive to frequencies higher than 1.5 Hz because of the grid spacing used. In terms of spectral shapes, it is possible to conclude that the modeling of sites 2, 3, 4, 5, and 6, produced by the two codes, presents similar results considering the general envelop of amplification functions.

As a final step, we compared modeling results with spectral ratios derived from microtremor data at AQPK and GDIF. Figure 10a shows QUAD4M and BESOIL results for AQPK compared with the strong-motion H/V ratio evaluated on *S*-wave and coda windows, the H/V ratio evaluated from the microtremor data, and SR spectral ratios from

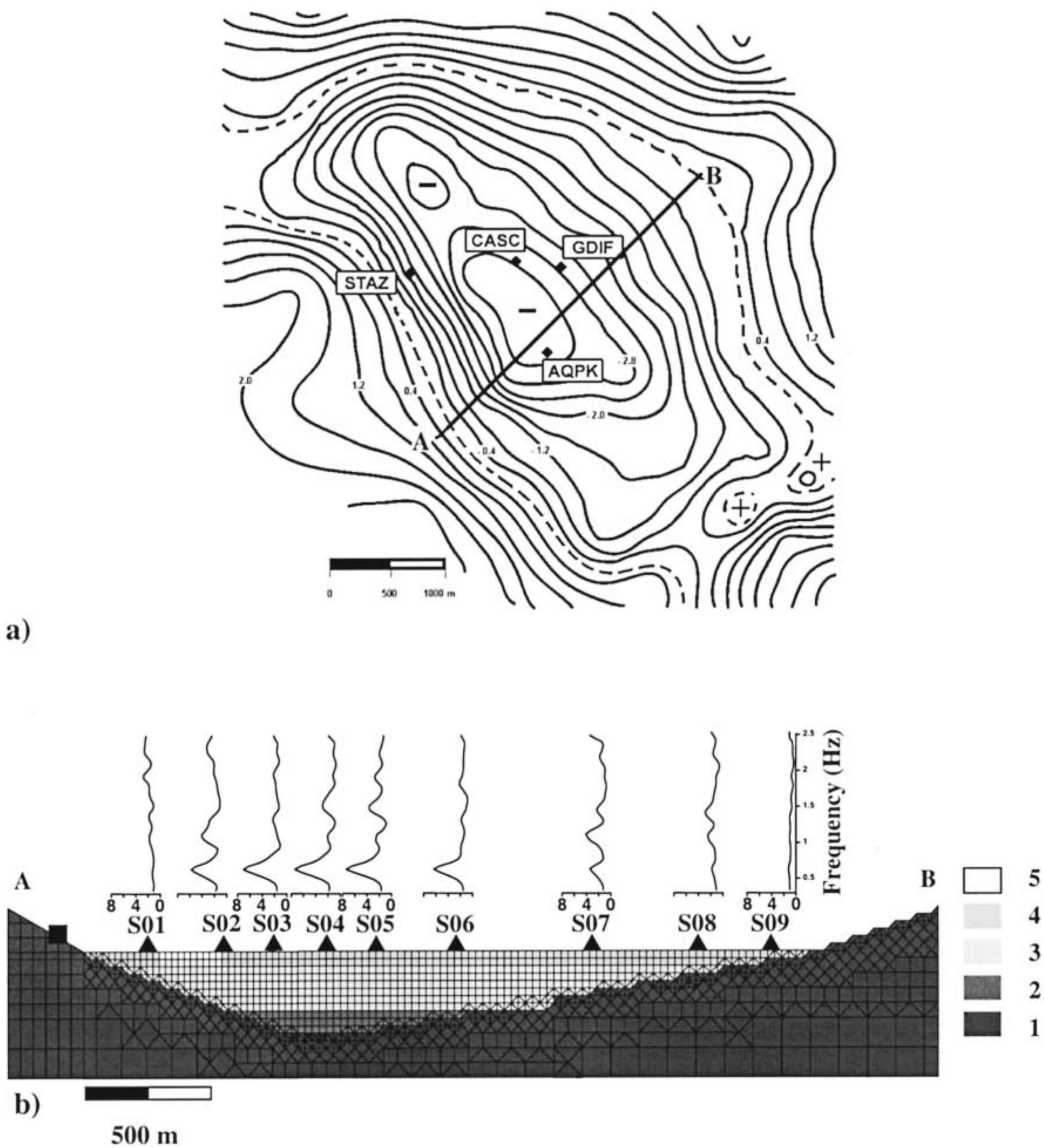

Figure 9. Sketch of the geometry of the L'Aquila basin. Figure 9a shows Bouger anomalies, expressed in mGal, along with microtremor recording sites and the location of line AB, used in numerical modeling. Figure 9b shows the geological cross section AB along with the finite elements grid. Geological units are indicated as follows: Aterno River recent deposits (5), megabrecce (4), uppermost lacustrine clays (3), lower lacustrine clays (2), limestone (1). The square represents the location of the rock site used as a reference site. Triangles represent the sites used for evaluating the amplification functions plotted in the upper part of the figure. The horizontal and vertical scales are the same.

weak-motion data. Modeling and microtremor results are also represented for GDIF in Figure 10b. A clear general agreement was found in all the represented data for the frequency range considered in this paper. This confirms that the modeling used is able to reproduce the major ground-shaking characteristics in the low-frequency range (<1.0 Hz).

Conclusions

The purpose of this work was to combine different approaches to site-response estimation and evaluate the effect of surface geology on ground motion in an urban area.

We tried to achieve our objective by using different types of experimental data collected during 1996–1999. The

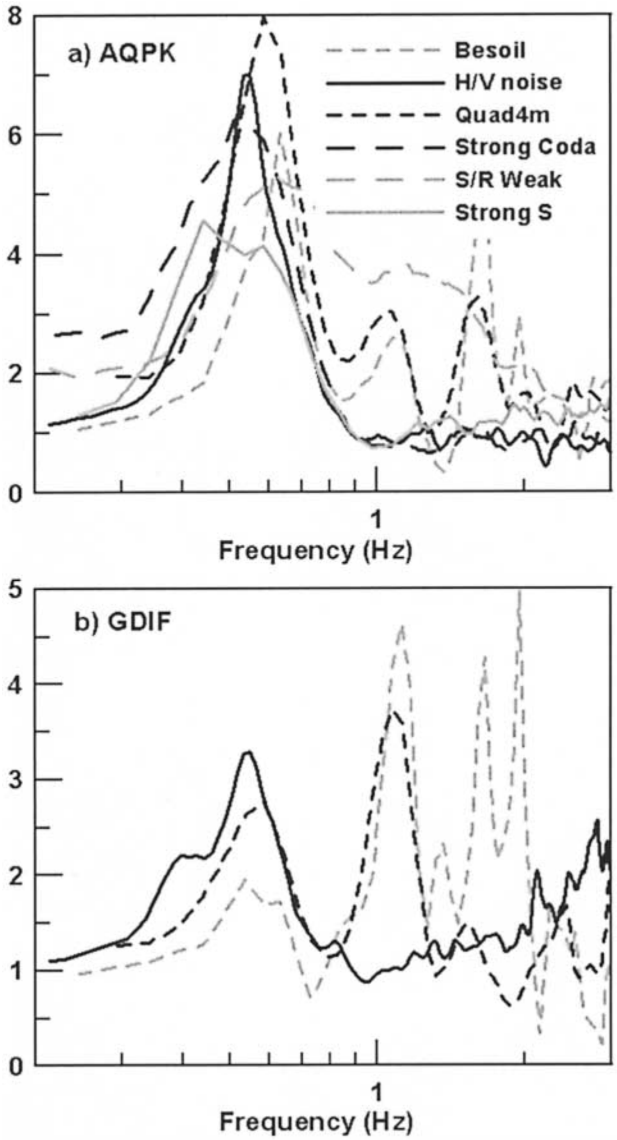

Figure 10. (a) QUAD4M and BESOIL solutions compared with H/V applied to strong-motion and microtremor data and S/R applied to weak-motion data at the AQPK site. (b) QUAD4M and BESOIL solutions compared with H/V applied to microtremor data at the GDIF site. The line symbols are the same in both (a) and (b).

work is not intended to be a microzonation of L'Aquila since its purpose was to understand the important low-frequency site response found in experimental ground-motion data following the first installation of seismic monitoring systems in 1996.

To solve the problem, we decided to perform a wide set of measurements to overcome the ambiguities inherent in various empirical approaches. The presence of an important amplification factor in the low-frequency range (0.5–0.6 Hz) was confirmed by all the collected data. Owing to the amplitude of the input ground motion used, we were not able to discriminate any nonlinear effect, since the maximum measured peak ground acceleration was only 10 cm/sec^2. A simple 2D model based on gravity data, for the assessment of the geometry of the basin, and on SASW data, for shear-wave velocity estimation, was sufficient to reproduce the experimental results, at least in the low-frequency range.

The low-frequency amplification effect was modeled using two different approaches, based on finite and boundary element methods. Both methods produced results similar to those observed in the experimental data.

The stability of the amplification effects in terms of frequency throughout the historical city center suggests that the thickness of the sedimentary basin is quite constant in the area. Some noticeable changes both in resonance frequencies and in amplification factors can be expected near the edges of the basin, as shown by the data collected at the railroad station and by the numerical modeling. These effects need future investigations.

Because of the characteristics of the buildings found in the investigated area, mainly old masonry buildings, the low-frequency amplification does not really affect their behavior during earthquake shaking. This consideration does not hold for new expansion areas, residential and industrial, where some tall concrete buildings have recently been constructed. An important issue involves the recent use of seismic base isolation for strategic buildings. Seismic isolation produces, as a first result, a shift in the building response toward the low-frequency range, around 0.5 Hz. It is obvious that this can in some cases result in a resonance with site response.

The research carried out in the city of L'Aquila represents an important step in the evaluation of local site effects in urban areas both because of the relevance of the city and because its geological setting is quite common in the Apennine seismic belt. We were able to show that, in seismically active areas, it possible to collect good-quality data in a short time period to use as a basis for microzoning purposes as well as for testing numerical modeling of site amplification.

As a final consideration, we believe that our results offer useful information for seismic risk assessment in the city and can provide a basis for the design of new buildings.

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