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A study of local site effects in Benevento (Southern Italy) by the analysis of seismic records of explosions

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Abstract
In this paper we evaluate the seismic amplification effects in the town of Benevento using records of an explosion of 500 kg fired at about 7 km. Seismic records were obtained at 43 selected sites in the city by digital three-component stations. A data selection performed on the signal-to-noise ratio reduced the available data to 26 stations. We used the spectral ratio techniques to evaluate the amplification effects of each recording site compared both to the average spectrum calculated over 26 stations and to a reference seismic station. The shapes of the spectral ratios were classified according to the geological characteristics of the site. A characteristic shape of the spectral ratio was observed to be related to the specific structure of the subsoil. In particular, the sites on basin sediments (Lagonegro Unit) and Middle Pleistocene conglomerates failed to show amplification effects; the sites on thick alluvial deposits showed amplification in the 5-9 Hz range; finally, sites on alluvial-lacustrine deposits amplified the seismic signal at frequencies depending on the characteristics and the thickness of the deposit. In addition, damage distribution caused by the 1688 earthquake in Benevento was related to the thickness of the surface layers in the ancient built-up area of the town. The study of the spectral ratios showed that these deposits amplify ground motion at frequencies between 9 and 12 Hz, *i.e.* frequencies close to the natural period of the most widespread buildings at that time in Benevento. Geological and seismic data were jointly used to carry out a zonation of the urban area of Benevento on the basis of homogeneous seismic responses. The validity of this analysis is limited to the main frequency band and amplitude of ground motion produced by the explosions.

Key words *site effects – spectral ratio – Southern Apennines – Benevento*

1. Introduction

The town of Benevento is located in the Southern Apennines about 50 km NE of Naples, in the Sannio area (fig. 1). The town was established by Pre-Roman Italic populations. The Amphitheatre and the magnificent Triumphal Arch witness the importance of the town in the Roman Age. During the centuries following the fall of the Roman Empire, under the rule of the Longobards, the dukedom of Benevento became one of the most important states of southern Italy. The construction of imposing city walls, at present delimiting the ancient built-up area, dates back to this period (11th century). At first the town was developed

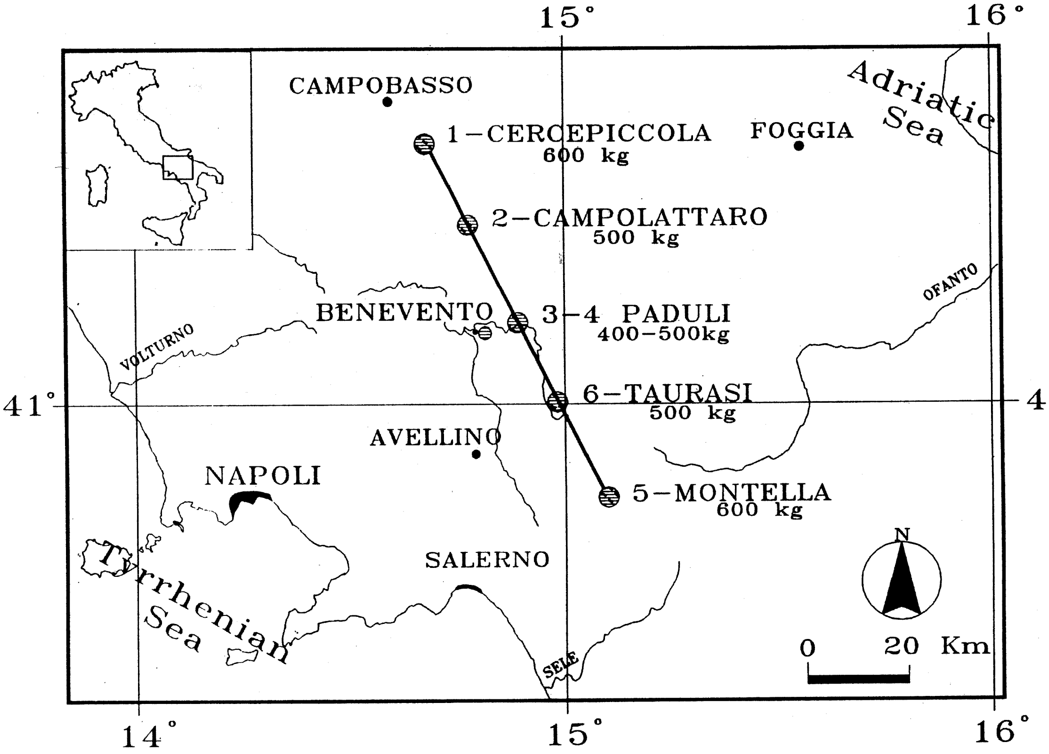

Fig. 1. Map showing the location of Benevento. The seismic refraction profile performed in October 1992 is shown. Circles represent shot sites and respective weights.

on a hill at the confluence of the Sabato and Calore rivers; over the last few decades, the town has spread in the valley between the two rivers. At present it has about 60000 inhabitants.

During its long history, Benevento was frequently struck by earthquakes which caused serious damage and numerous victims. One of the most destructive events of the seismic history of Italy occurred in 1456, causing the death of about 30000 people and intensity MCS IX over a 20000-km^2 area. Benevento suffered MCS intensity IX-X. The earthquakes of 1688, 1702 and 1732 caused damage corresponding to IX-X MCS (Postpischl, 1985). Among them, the best documented is the 1688 earthquake. For this event the damage map of the Benevento town has been reconstructed by Castenetto and Romeo (1992).

During this century, the seismicity of the Sannio area has been characterized by low-energy earthquakes, which have often occurred in swarms (Scarpa and Zollo, 1985). The recurrent large historic earthquakes in the Sannio region along with the present low seismicity level suggests that this region may have one of the highest seismogenic potentials in the whole of the Apennines.

With the aim of performing a seismic hazard analysis of the Benevento region, a multidisciplinary research program was supported by the Commission of the European Communities (Marcellini *et al.*, 1991). This program included an active seismic survey that was carried out in Southern Apennines in October 1992. The main goals of this survey were the following:

– to improve knowledge of the upper crustal structure in order to define a *P*-wave velocity model to be used in seismological studies;

– to evaluate site response effects in Benevento using shot records.

The field procedures of the October 1992 experiment are described in a technical report edited by *Gruppo Acquisizione Dati Sismici Progetto Benevento* (1994).

Short-period ground motion records from small local earthquakes or other natural or artificial sources that produce microtremor are commonly applied to estimate site effects. Widely used techniques involve either direct interpretation of amplitude spectra to evaluate the dominant period of soft soil sites (Katz, 1976) or studies of spectral ratios using a reference signal from a bedrock site (Field *et al.*, 1990). The large number of applications show the validity of using microtremor for estimating the site response (*e.g.* Lermo and Chavez-Garcia, 1994). Likewise, microearthquake records have been repeatedly employed for site response evaluation (Field *et al.*, 1992; Hartzell, 1992).

In this paper, we used ground motion records induced by artificial sources to study site effects in Benevento. In particular, we analyzed the seismograms recorded by 43 three-component digital stations operating in the town of Benevento during the active seismic survey of October 1992. We applied the spectral ratio technique to estimate relative response spectra. Spectral ratios between each recording site and a reference site were correlated with the local geological characteristics. We were able to identify areas with distinct spectral characteristics and then to produce a soil amplification map of the Benevento town. Finally, a comparison was made between the results of this analysis and damage distribution of the 1688 earthquake.

2. Geology of Benevento

Early Benevento was located at the confluence of the Calore and Sabato rivers on a terrace consisting of ancient clastic deposits; the alluvial plains of the two rivers have recently been intensely urbanized (fig. 2). The Calore and Sabato rivers are the main agents modelling the landscape; alternating sedimentation and erosion cycles, they caused the accumulation of considerable amounts of alluvial deposits and the formation of terraced surfaces.

The area under investigation is a Plio-Pleistocenic tectonic depression filled with marine and continental deposits. Most of the pre-quaternary substrate is formed by Pliocenic marine sediments of the Ariano Unit (Middle Pliocene) overlying the flysch of the Meso-Cenozoic Lagonegro Basin. Geophysical data show that the terrigenous deposits of the Ariano Unit reach their maximum thickness (250 m) in correspondence of the Sabato river valley; they have never been subjected to intense deformation and are tilted into a simple monoclinal structure dipping towards N-NE (Pescatore *et al.*, 1995).

The flysch of the Lagonegro Unit crops out NE of Benevento (fig. 3). It consists of stiff and deeply deformed marl and shale with layers of sandstone; generally, a thick layer of weathering, formed by loose to dense sand and soft clays, covers these deposits.

The deposits of the Ariano Unit include terrigenous successions formed by clay, sand and sandstones interspersed with conglomeratic layers. In the Sabato river valley the sedimentary substrate is formed by *blue clay* with thin and stiff silty levels. Here, the top of the Pliocenic formation lies at an elevation of about 120 m a.s.l. and progressively dips to 80 m a.s.l. towards the confluence with the Calore river. Along the Calore river valley the pre-quaternary substrate becomes more depressed, due to tectonic displacements.

Pleistocenic deposits in the Benevento area consist of thick alluvial and fluvio-lacustrine successions witnessing overflow events and formation of small basins in tectonic depressions. These soils cover the sedimentary substrate. The Pleistocenic sediments, which often reach a thickness of several tens of meters (fig. 4), show marked differences in their lithological and mechanical properties; on the basis of these differences, three main formations

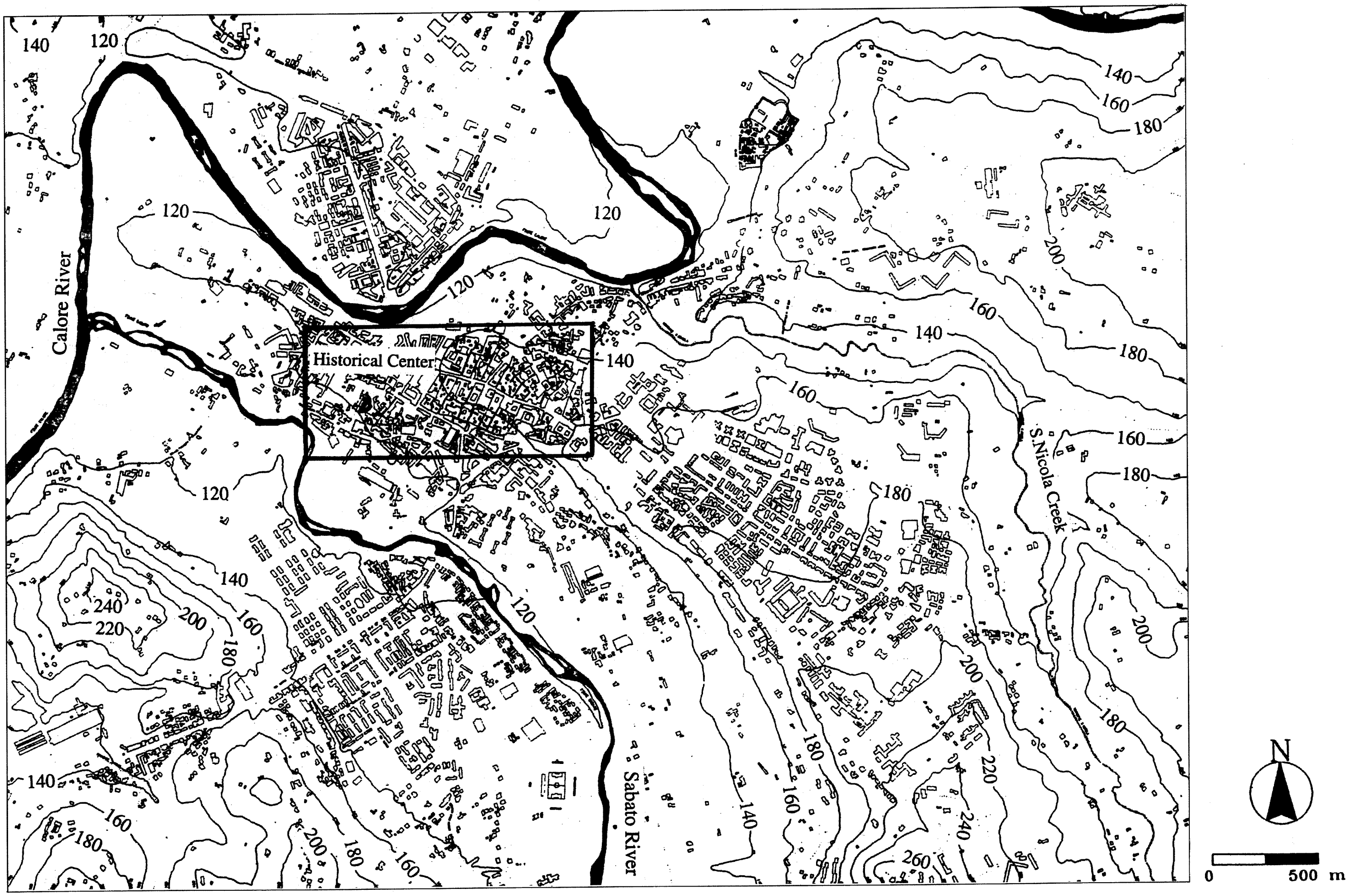

Fig. 2. Topographic map of Benevento town. The area included in the box represents the ancient built-up area shown in fig. 10a,b.

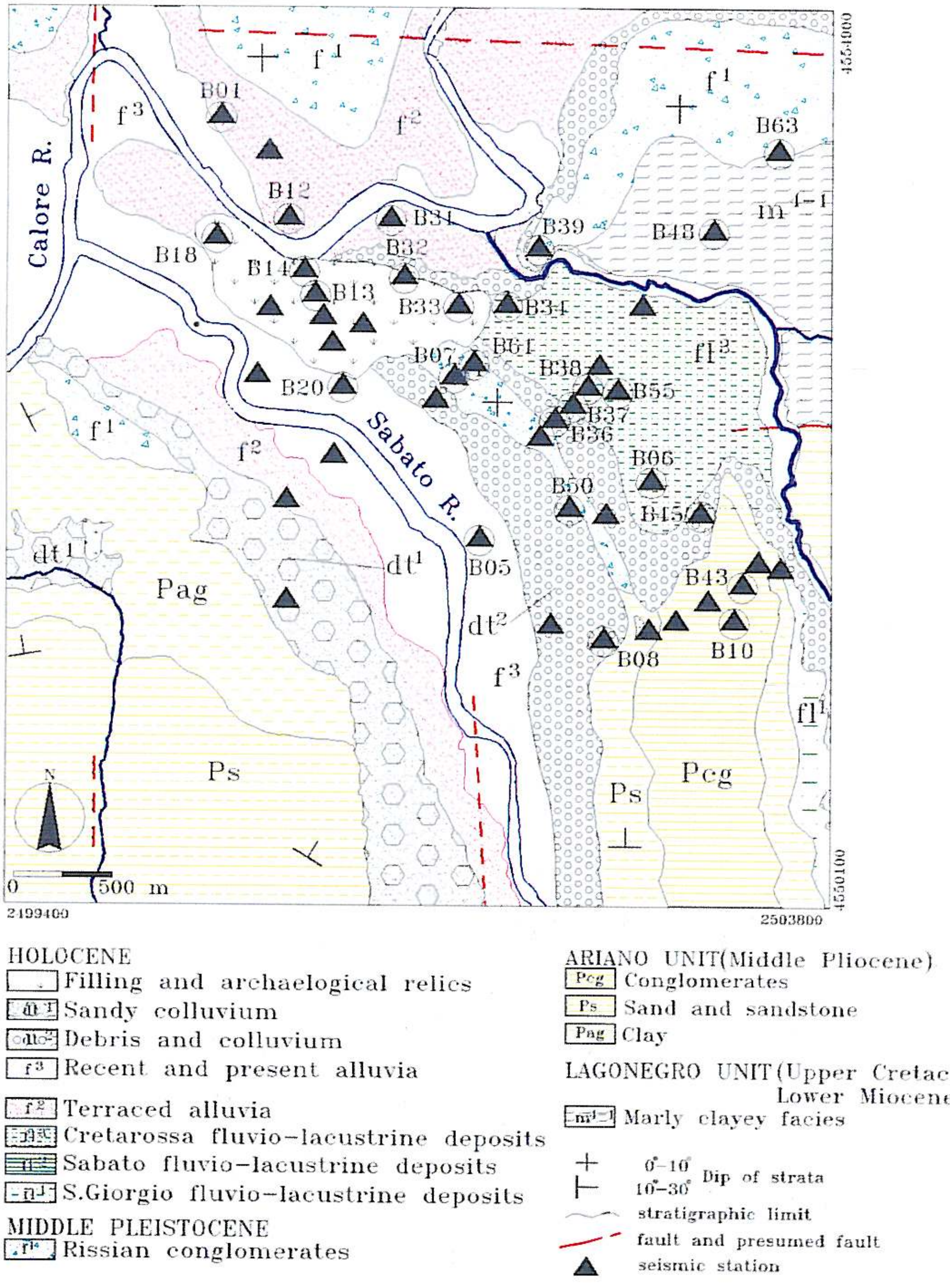

Fig. 3. Geological map of Benevento. Triangles represent seismic stations operating in Benevento. Circled-triangles are stations with acceptable signal to noise ratio used in this paper.

can be distinguished:

- *Middle Pleistocene conglomerates (Rissian conglomerates)*;
- *fluvio-lacustrine deposits*;
- *Late Pleistocene terraced alluvia.*

The ancient built-up area of Benevento is located on clastic deposits (cemented conglomerates with sand lenses) of the Middle Pleistocene (Riss). The conglomeratic formation crops out along the valley of the Calore river (fig. 3) to form terraces rising 70-80 m above the present level of the river. The thickness of the succession that overlies the Pliocenic clays exceeds 100 m. Fluvio-lacustrine deposits are predominant in the area south east of the town and along the western side of the Benevento hill. S. Giorgio basin formation and the Cretarossa succession crop out SE of Benevento. They are formed by a quite complex and rather chaotic layering of silty and clayey soils interbedded with dense gravelly materials; these soils, overlying the Rissian conglomerates or the Pliocenic substrates, reach a thickness of about 40 m (fig. 4).

The fluvial-lacustrine succession of the Sabato river, along the western marginal area of the Benevento hill, does not crop out since it is covered with debris and colluvial soils. It is primarily composed of thinly stratified clay with sandy layers with high organic content, and overlies the Pliocenic substrate. It does not exceed 40 m in thickness (fig. 4). In the Calore river valley, terraced alluvia (dense and sometimes cemented gravels with silty to sandy

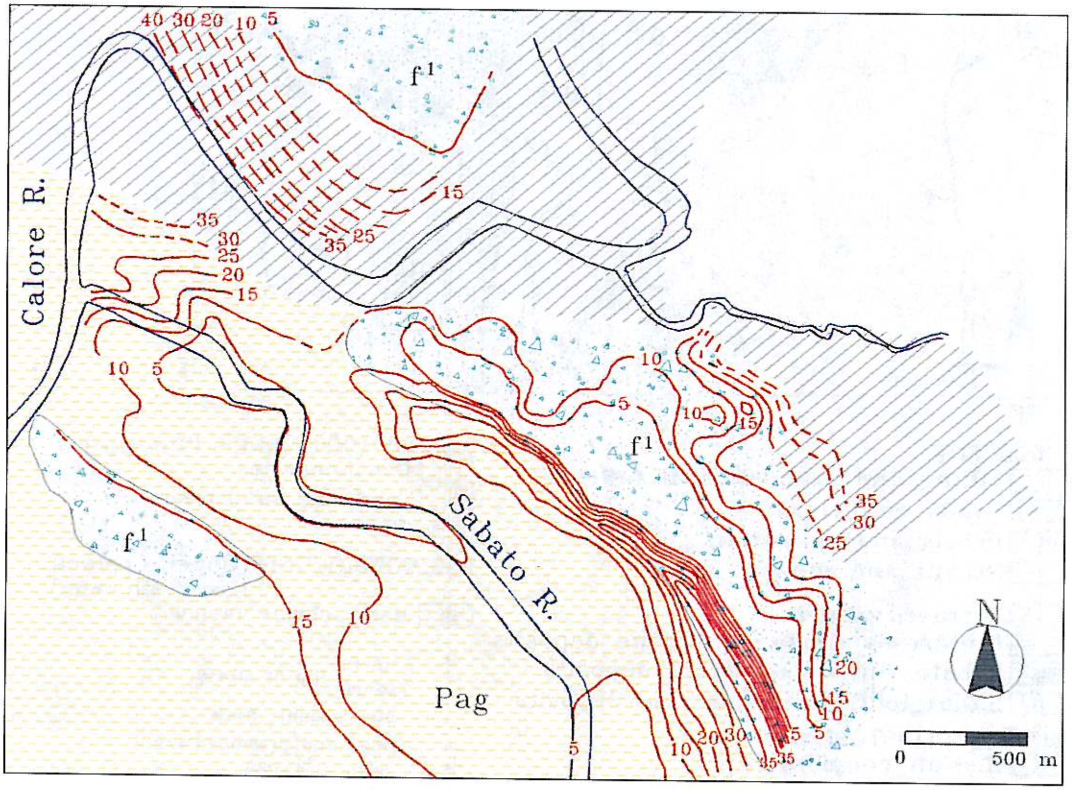

Fig. 4. Isopac map of the post-rissian sediments (in meters). Hypothetical contours are dashed. Shadow zones indicate areas where the lithology of the substrate is unknown. The symbols are the same as in fig. 3.

lenses) are predominant. They are no less than 40 m thick (fig. 4), and are overlaid by looser and uncemented *recent alluvia*. The recent alluvia, instead, represent the main shallow deposits of the Sabato river valley, where the thickness is no more than 10 m (fig. 4).

Generally, *debris*, *colluvial soils* and *pyroclastites* cover the formations described above.

Debris and colluvial deposits are present along the hillside slopes down to variable depths, reaching a maximum thickness of about 20 m. They are formed by a coarser fraction, deriving from the disintegration of the Rissian conglomerates, in a finer matrix resulting from the weathering and remoulding of former pyroclastic materials. The pyroclastic materials can be retrieved as lenses of a few meters of ashes (from Campi Flegrei) and pumice (from Vesuvius), deposited in ancient depressions as the result of large eruptions.

In the old part of Benevento the shallowest soils consist of *man made ground* (filling material and archaeological relics) that sometimes reaches a thickness of about 10 m (Pescatore *et al.*, 1995).

3. Analysis of seismic records performed in the town of Benevento

3.1. *Field procedure*

The seismic survey of October 1992 involved six shots in five different sites located along a profile oriented approximately in the Apennine direction (fig. 1). Two different receiver configurations were deployed to record the shots:

– a linear network along an 80-km-long profile to model crustal features;

– a local network with stations located on various geological formations characterizing the subsoil in the town of Benevento for site response studies, which are reported here.

For the latter, ten seismic stations recorded shots 1, 2, 3, 5, 6, while 43 stations were installed to record shot 4; this shot was performed near the Calore river at about 7 km east of Benevento, using 500 kg of explosive (*Gruppo Acquisizione Dati Sismici Progetto Benevento*, 1994). Figure 3 shows the location of the stations. Each station was equipped with a digital three-component system: 23 stations had Mark-L4C geophones with a natural frequency of 1 Hz, and 20 stations were equipped with Mark-L22 geophones with a natural frequency of 2 Hz. All the instruments had been previously calibrated; the sampling frequency used was 125 or 200 sps. The time interval used for recording each shot was about 8 min. During the recording of the explosions, with the cooperation of the town authorities, road and rail traffic was completely stopped to reduce the seismic noise.

The recording sites were selected on the basis of the following criteria:

– dense covering of the whole area studied;

– location on areas where borehole tests had been performed for civil engineering works, in order to have an accurate reconstruction of the subsoil structure;

– location on various geological formations which characterize the Benevento subsoil.

Improta (1994) has given a detailed description of the geology, including lithostratigraphic columns at most of the recording sites.

3.2. *Selection of data*

Data selection was based on the signal-to-noise ratio. The amplitude spectra of shot records were compared with those of seismic noise computed from a 5-s time window recorded just before the shot. A threshold value of 5 was fixed for the ratio of the two spectra. The spectra were computed by applying the FFT code to a selected time window which had been previously 10% cosine tapered. These time windows were about fifteen seconds, starting one second before the first *P*-wave pulse. Such a long time window was preferred to include all the important wave trains and to include the entire spectral range of interest. The coda of the seismograms which is probably dominated by surface waves, contains longer period waves than the early part of the seismogram which is dominated by body waves. The time window of 15 s extends the lower limit of the spectra to 1 Hz, above the noise level at these frequencies. Otherwise, if the analyses are performed using a short time window (2 s) centered on the body waves, the low frequency limit is 4 Hz (fig. 5).

We analyzed the Fourier spectra of the two horizontal components of ground motion. The average horizontal spectrum was calculated as the square root of the sum of the squares of the spectra of the E-W and N-S components. To reduce fluctuations in the spectral shapes, each spectrum was smoothed by calculating the running average computed over ten points. The ratio between the spectra of shots and microtremor tended to cross the threshold value of five at 12 Hz. The microtremor contribution increases at frequencies higher than 12 Hz. At low frequencies the spectral analysis was restricted to ≥ 1 or ≥ 2 Hz depending on the geophone used (Mark L4-C or L-22 respectively).

Based on this criterion, 26 seismic records were selected for the analysis (fig. 3).

3.3. *The reference site*

Figure 6 shows the seismograms recorded at five sites characterized by different geological conditions. The E-W components (which correspond to the radial direction) are shown together with the stratigraphic columns of the recording sites. The ground motion on alluvial deposits (station B01), fluvial-lacustrine deposits (B06) or filling material (B18) is remarkably amplified compared to ground motion on the Pliocenic clay (B05) or on Rissian conglomerates (B07).

The complex geological structure of the Benevento subsoil showed the lack of a firm soil that we can assume as high impedence rock in site response studies (Pescatore *et al.*, 1995). In fact, the dynamic properties of Pliocenic clay, which represents most of the pre-pleistocenic substrate in the studied area, show low values of shear wave velocity ($Vs = 600$ m/s). The Miocenic flysch of the Lagonegro Unit, cropping out NE of Benevento, is characterized by similar values of velocity because of weathering. Moreover the Lagonegro deposits display a wide variability in the lithostratigraphic characteristics. Although in some sites on Rissian alluvial deposits large values of shear wave velocity can be found ($Vs = 1500$ m/s), conglomerates are very heterogeneous. In fact, they often include layers of loose conglomerates and sandy lenses which significantly reduce the values of Vs, to values of about 500 m/s (Improta, 1994).

The difficulty in identifying a reference site on the basis of geological and geotechnical information therefore, suggested carrying out analysis of the spectral ratios using as reference spectrum:

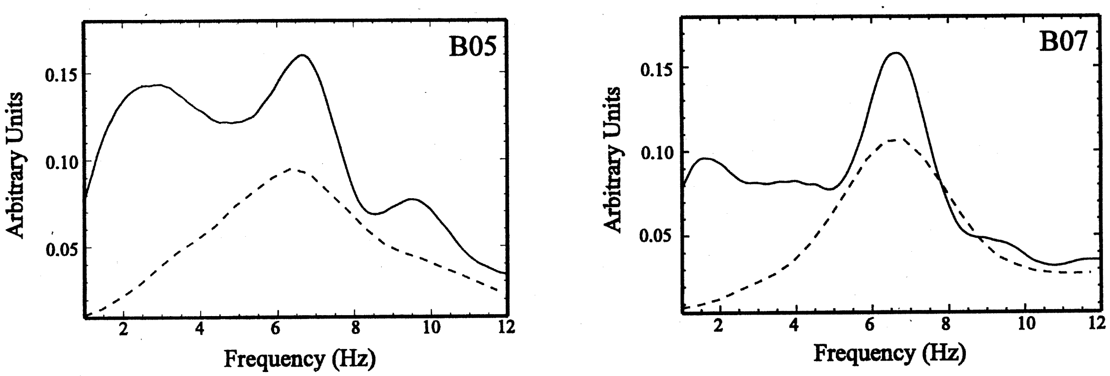

Fig. 5. Amplitude spectra computed using two different time windows: 15 s continuous line, 2 s dashed line.

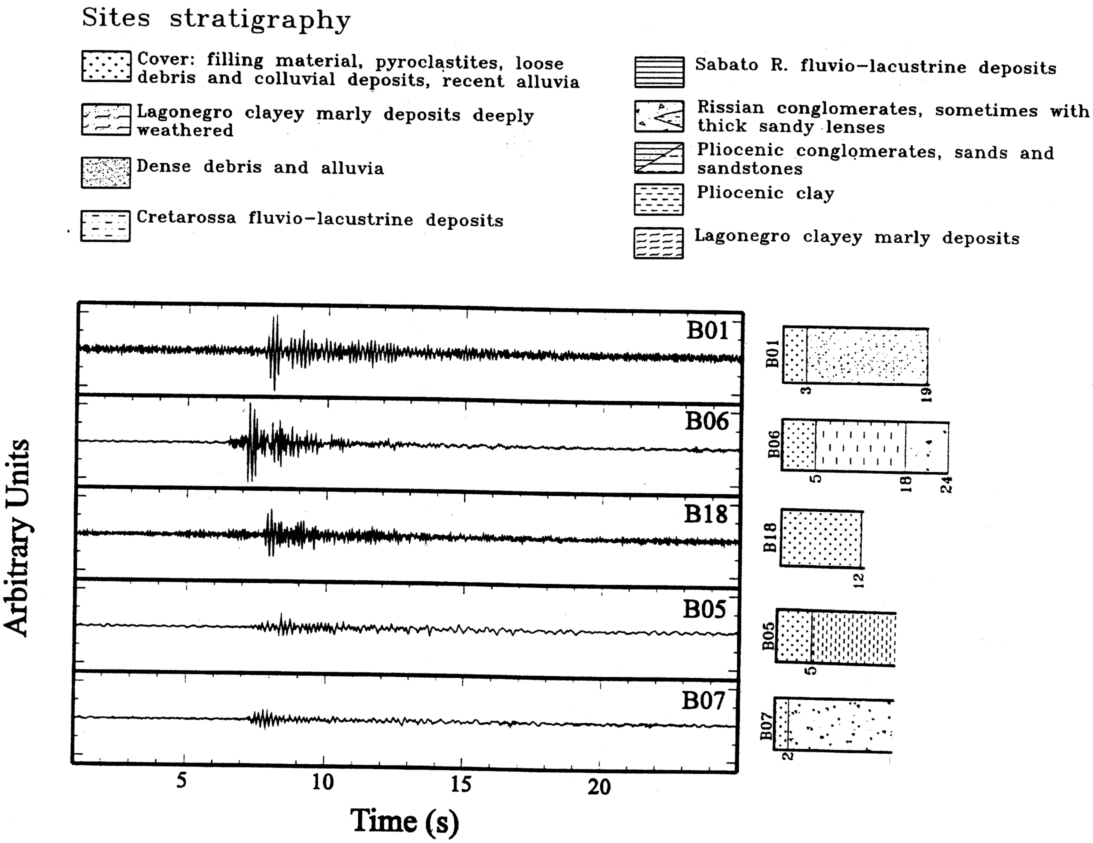

Fig. 6. Plots of the E-W component of 5 seismic stations located in areas with different geological conditions (see fig. 3). The stratigraphic columns of the recording sites are also indicated (depth in meters).

a) the average spectrum calculated over 26 stations,

b) the B36 station, located on Rissian conglomerates.

In fact, eliminating fluctuations in the spectral shapes characteristic of the recording site, the averaging of the spectra enhances of the source effects shared by all records. The analysis of Fourier spectra at 26 stations showed that the B36 station has a rather simple spectral shape without anomalous peaks due to site resonance effects. Therefore, this station situated on Rissian conglomerates was also chosen as the reference station. Figure 7 depicts the average spectrum and the spectrum of station B36.

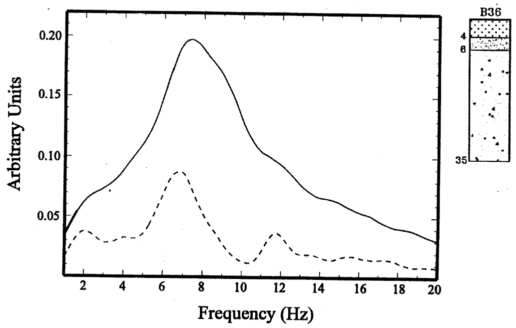

Fig. 7. Comparison between the two selected reference spectra: B36 spectrum dotted line; average spectrum continuous line.

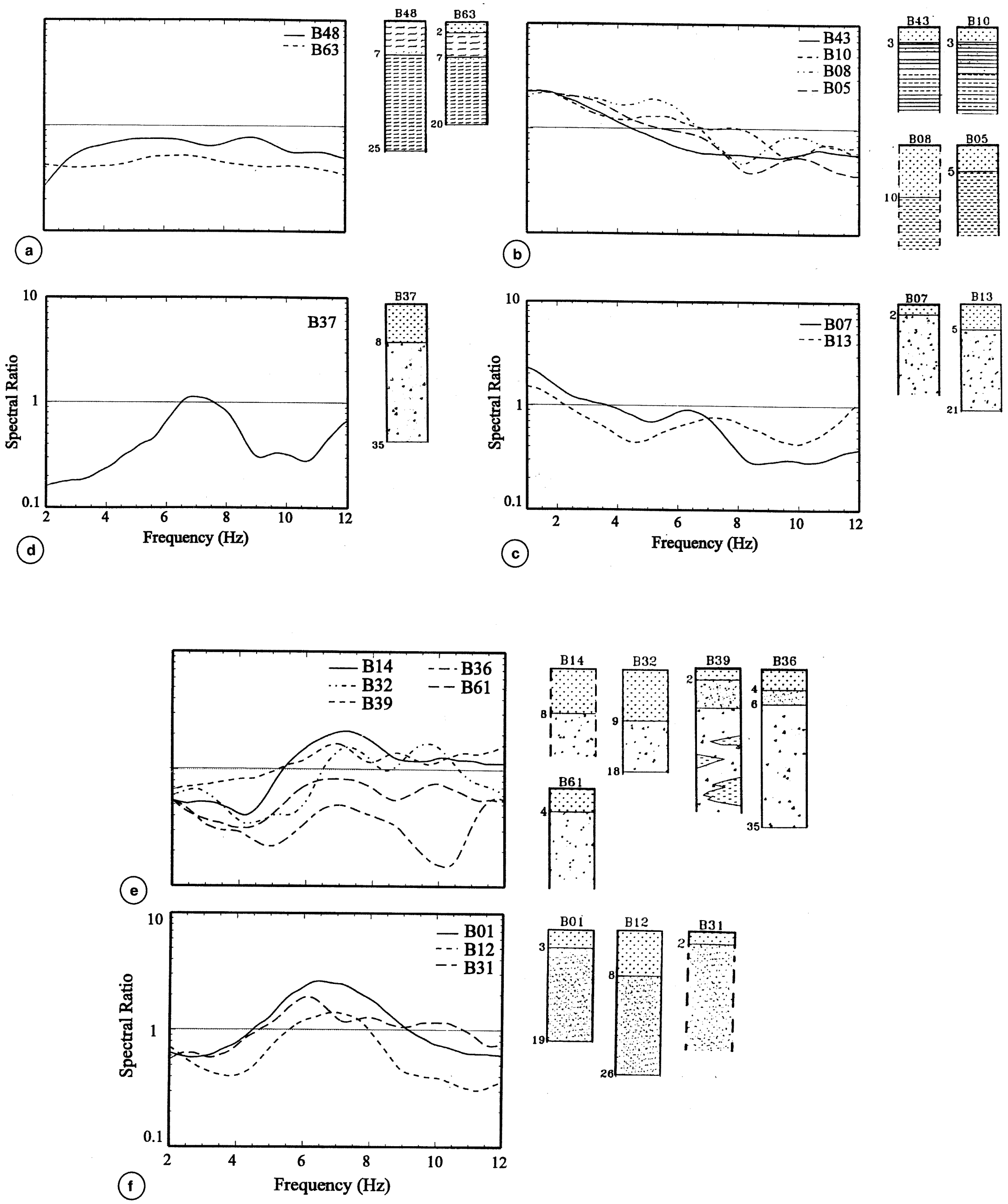

Fig. 8a-f. Spectral ratios computed with respect to the average spectrum. The spectra are grouped according to similar site geology (see the text).

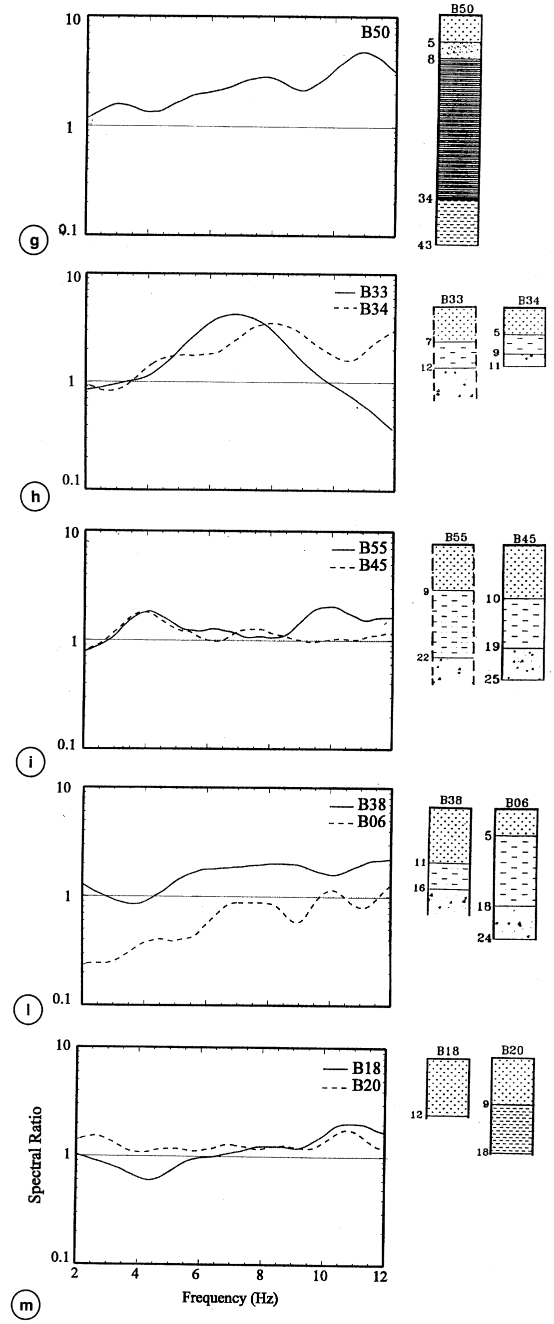

Fig. 8g-m. Spectral ratios computed with respect to the average spectrum. The spectra are grouped according to similar site geology (see the text).

3.4. *Spectral ratios*

A preliminary analysis was performed to determine the spectral ratios between individual sites and the average spectrum. The spectral ratios were grouped on the basis of the geological similarity of the sites (figs. 8a-m). It can be noted that:

– sites B63 and B48, situated on clayey marly sediments of Lagonegro Units, showed a clear attenuation effect at all frequencies (fig. 8a);

– sites on the Pliocenic deposits showed a slight amplification effect (about 2) at low frequencies (1-4 Hz). At site B08, located on the thickest surface deposits, the amplification effect extends to 6 Hz (fig. 8b);

– the sites on Rissian conglomerates did not provide homogeneous responses; this may be due to the aforementioned heterogeneity of the deposit, at least for low frequencies. However, we observed attenuation of the seismic motion between 3 and 6 Hz, and its amplification at higher frequencies when cover soils were present (debris and colluvial soils, weathered pyroclastic layers, filling material) (fig. 8c,d,e).

– sites B01, B12 and B31, located on alluvial deposits of remarkable thickness, amplified the seismic motion between 5 and 9 Hz, with peaks in the 6-7 Hz range (fig. 8f);

– site B50, the only one located on the fluvial-lacustrine deposits of the Sabato river, exibited amplification effects at all the frequencies, with a marked peak (about 5) at 11 Hz (fig. 8g);

– several sites on surficial soils and on the Cretarossa fluvial-lacustrine deposits showed different site responses. Sites B33 and B34 showed an amplification of about 4 in the frequency range between 4 and 10 Hz (fig. 8h). Sites B45 and B55 displayed, instead, smaller amplification effects (no more than 2) at low frequencies (3-5 Hz). Site B55 showed another peak at 10 Hz (fig. 8i). Sites B06 (fig. 8l), directly on the Cretarossa fluvial-lacustrine deposits, showed slight amplification effects both at low frequencies (1-3 Hz) and at frequencies higher than 5 Hz, whereas, site B38 did not show amplification effects. The stratigraphy of these two sites, which is approximately known, cannot explain the shape of the transfer functions, differing from those at sites with similar lithostratigraphic conditions;

– sites B18 and B20, situated on a several-meter-thick cover formed by filling and archeological materials, slightly amplified the signal in the range between 10 and 12 Hz (fig. 8m).

Spectral ratios were re-analyzed considering the spectrum at station B36 as the reference spectrum. Significant differences between the shapes of the transfer function were not observed (fig. 9a,b). It appears evident, instead, that, using site B36 as the reference site, the amplification values were larger, in particular in the frequency range between 8 and 12 Hz (fig. 9a).

4. A comparison with damage distribution of the 1688 earthquake

The earthquake of June 5 1688 was one of the most destructive events that have occurred in the Sannio area. The macroseismic field of this earthquake has been described by several authors (Serva, 1981; Postpischl, 1985). Recently, Castenetto and Romeo (1992) have analyzed the archival material and produced a damage map of the Benevento town.

In this section, the damage distribution is related to the surface geology and to results of the spectral analysis.

Figure 10a,b shows that the areal distribution of the isopacs of the surficial soils (cover, recent alluvial deposits and fluvial-lacustrine

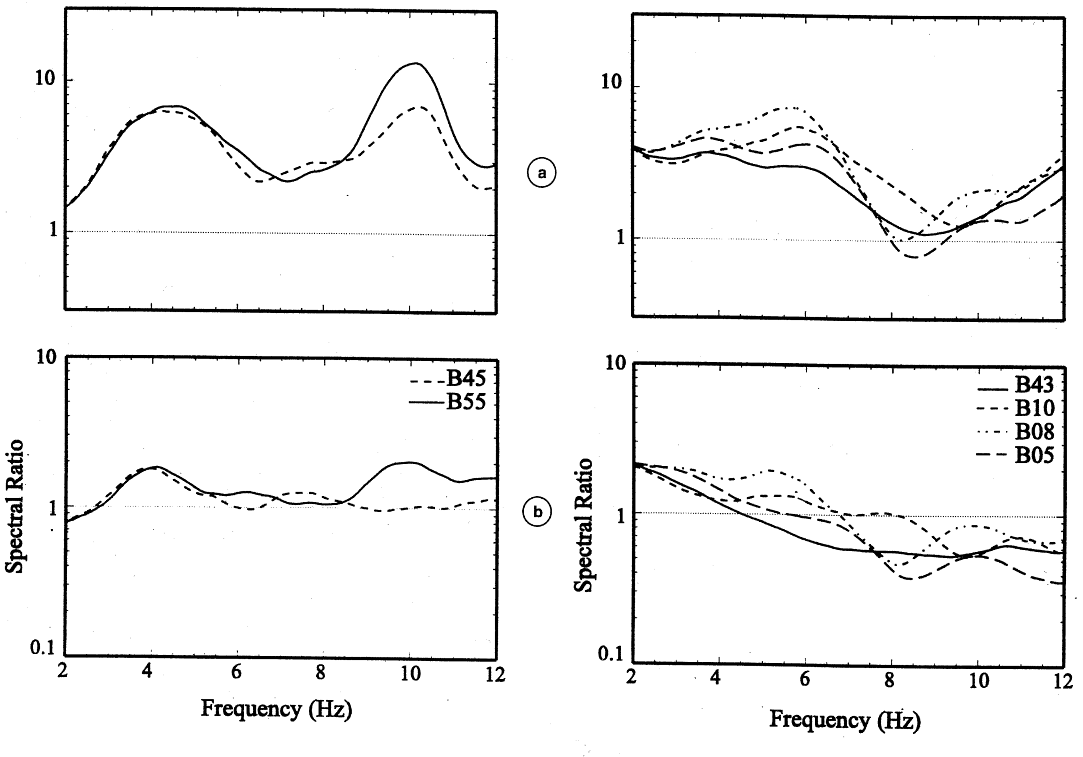

Fig. 9a,b. Comparison between spectral ratios computed by two different reference spectra: a) B36; b) the average spectrum of 26 stations.

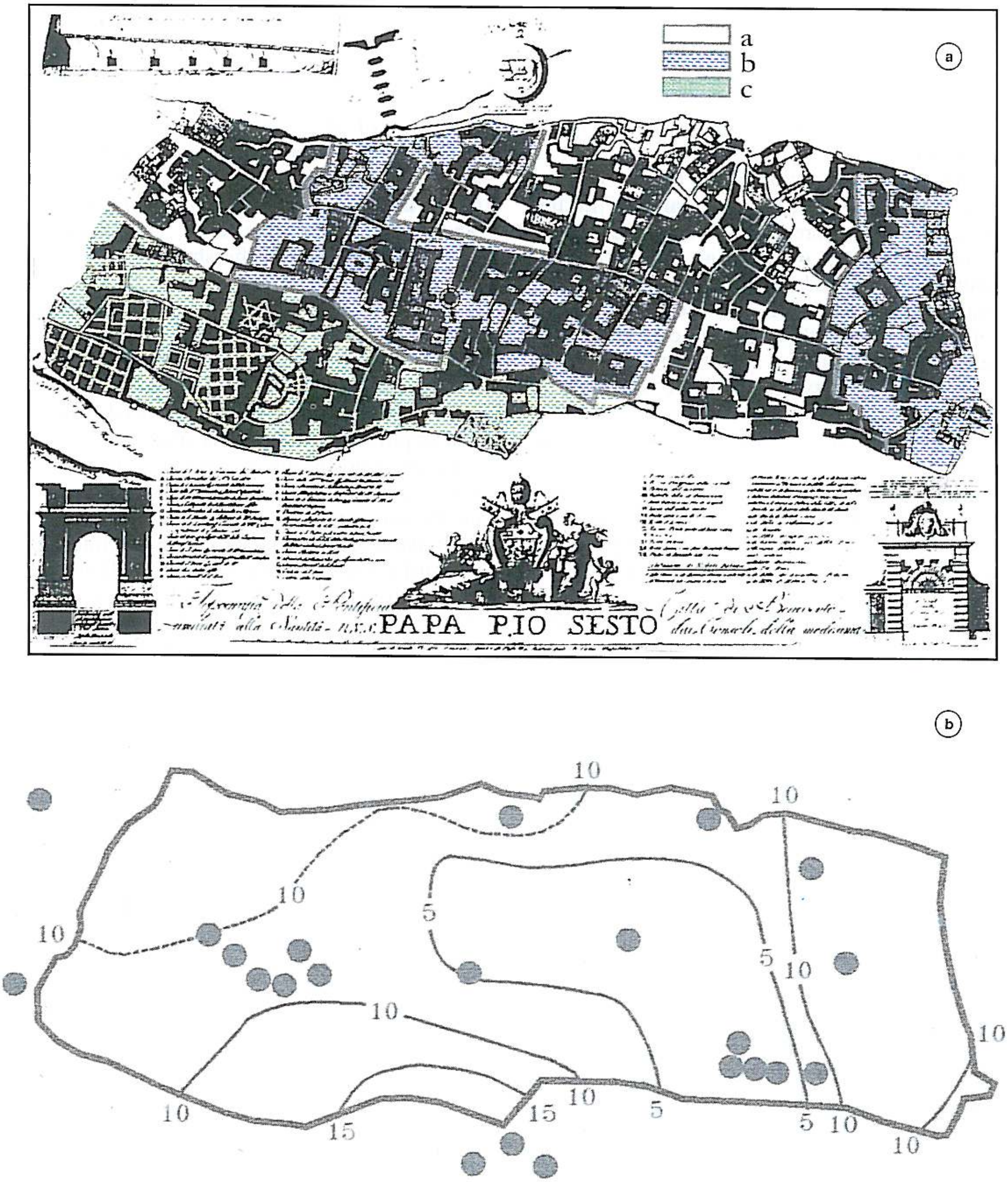

Fig. 10a,b. a) Map of the damage produced by the June 5 1688 earthquake in the town of Benevento (see fig. 2). Three levels of destruction can be distinguished: *a* - fewer than 50% of the buildings destroyed; *b* - between 50 and 75%; *c* - more than 75%. b) Isopac map of cover soils in the ancient town. Circles represent borehole locations. Hypothetical contours are dashed.

deposits) and the damage map are correlated. The areas where only few meters (≈ 5) of cover (filling archeological material, weathered pyroclastites, debris and colluvial soils) lie on Rissian conglomerates, appear relatively less damaged.

The southern portion of the ancient built-up area suffered, instead, great damage. In this area, numerous boreholes were drilled through more than 10 m of surficial deposits. These soundings showed that these deposits are mainly composed of fill, *i.e.* archeological material, and overlie the Pliocenic clay or the Rissian conglomerates.

Less damage occurred where the surficial deposits were less thick.

The low degree of damage observed in the western sector of the ancient built-up area contrasts with the thickness of the surficial soils (> 10 m). In this area, the isopac map deposits is uncertain, being based on stratigraphic data deriving from a single few-meter deep boreholes (Pescatore *et al.*, 1995).

Using a semi-empirical relation, Castenetto and Romeo (1992), estimated the natural period of the buildings for Benevento in the 17th century. Most buildings were estimated to have natural frequencies of about 10 Hz. Results from the analysis of the spectral ratios previously described show that recording sites where cover soils were more than 10-m-thick exhibited peaks at around 10 Hz (fig. 11).

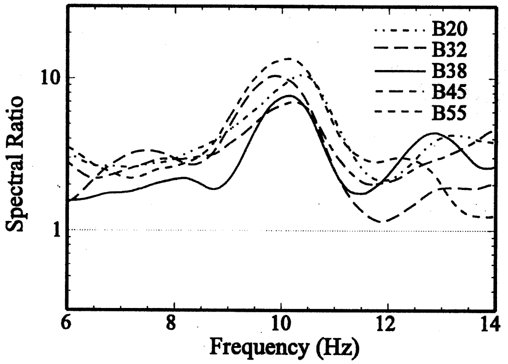

Fig. 11. Spectral ratios referred to sites with cover soils thicker than 10 m.

The simple model of one-dimensional near vertical *S*-wave propagation predicts that amplification effects due to the surface layer occur at a frequency $f = Vs/4H$. Assuming a layer thickness of $H = 5$-10 m and shear velocity $Vs = 200$-400 (Improta, 1994), this frequency is about 10 Hz. This evidence suggests that most of the damage in the southern part of the town was produced by resonance effects due to wave amplification in the shallow soils.

5. Discussion

The analysis of the seismic records generated by an explosion clearly showed differential amplification effects for areas where thick surficial deposits are present as compared to sites located on the pre-quaternary deposits or on Rissian conglomerates.

In particular, a detailed reconstruction of the sub-surface structure in the town of Benevento (Pescatore *et al.*, 1995) enabled us to relate characteristic spectral shapes to the geology of the site. This may result in a rough zonation of the urban area (fig. 12):

- the sites located on the Pliocenic deposits or in areas where the Pliocenic substrate is covered with a few meters of surficial deposits (valley of the Sabato river), show slight amplification effects at low frequencies (1-4 Hz) and attenuation of high frequencies, $f > 4$ Hz (area *a* in fig. 12);
- in areas with thick alluvial deposits, either dense or loose (valley of the Calore river), the ground motion is amplified in the range from 5 to 9 Hz (area *b* in fig. 12);
- the presence of cover soils more than 10 m thick produces amplification of ground motion at high frequencies (9-12 Hz).

Though similar in geological characteristics, sites on Rissian conglomerates do not show a homogeneous seismic response. Nevertheless, none of the transfer functions show amplification effects; therefore, it can be stated that the areas where the conglomerates are at very shallow depths (with the exception of the sites with more than 5 m of cover soils lying on the Rissian conglomerate) are generally not subjected to local amplification (area *c* in fig. 12).

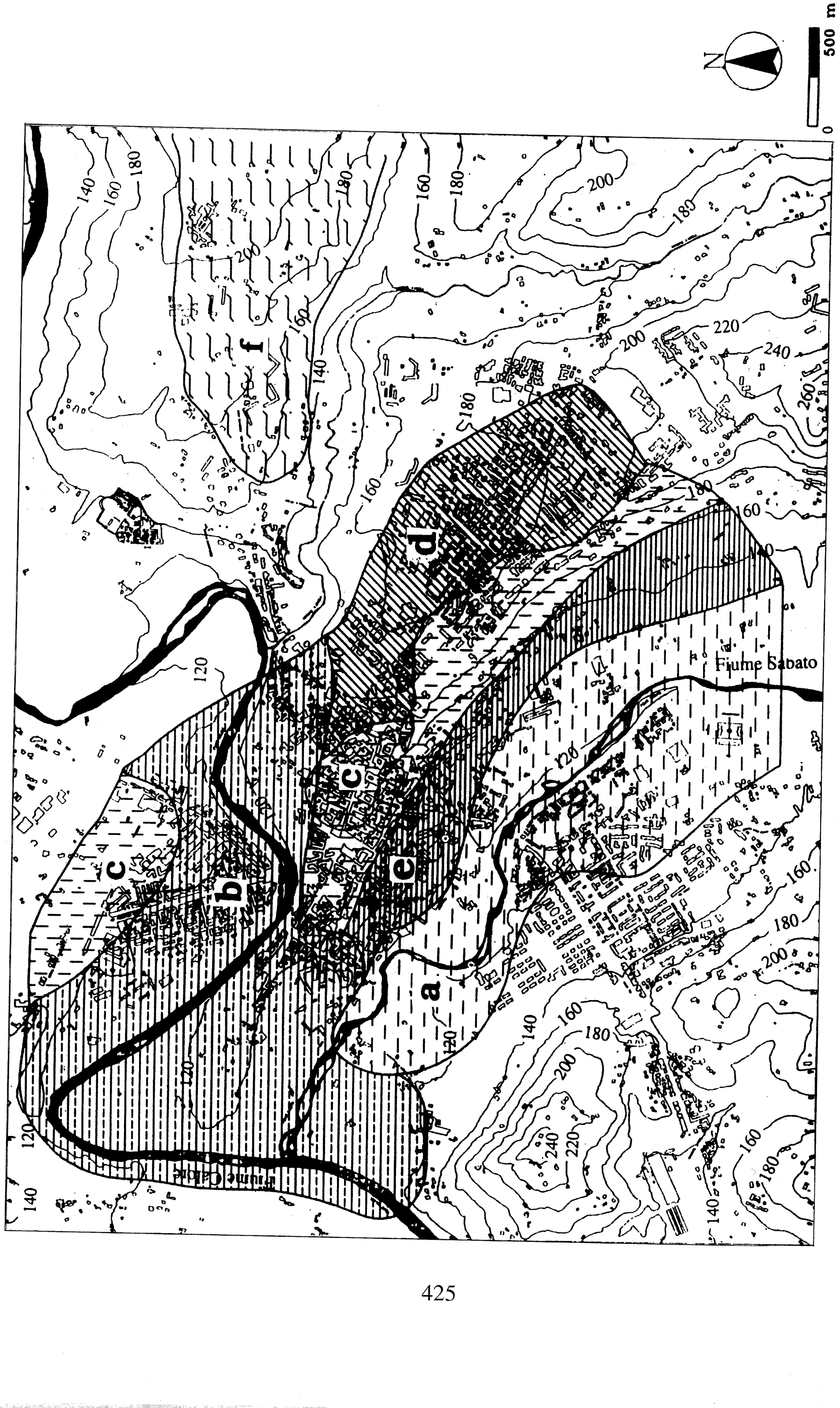

Fig. 12. Seismic amplification map of Benevento (see text).

– The sites on fluvial-lacustrine deposits always show amplification effects. The heterogeneity of the fluvial-lacustrine deposits and their varying thickness may be the cause of a differential seismic response at various sites (area *d* in fig. 12). In particular, site B50, located on the western margin of the Benevento hill, where the fluvial-lacustrine succession of the Sabato river is covered with several meters of debris and alluvial deposits, strongly amplifies ground motion, especially at high frequencies (10-12 Hz). This result might indicate that along the western margin of the hill strong amplification effects are expected (area *e* in fig. 12).

– Two records are available in the northeastern part of the studied area, where the Miocenic flysch crops out. Although data show no ground amplification, the two available spectral ratios cannot be considered representative of the whole area in which the Lagonegro deposits crop out because of the strong variability of the lithostratigraphic characteristics of these sediments (area *f* in fig. 12).

Finally, the damage caused to Benevento by the 1688 earthquake was correlated with the thickness of the surficial deposits; the spectral ratios showed that these soils amplify ground motion at frequencies ranging between 9 and 12 Hz, close to the natural period of vibration of most of the buildings in Benevento at that time.

6. Conclusions

In this paper, the effects of ground motion amplification due to local geology were evaluated for Benevento by analyzing the records of ground motion produced by 500 kg of explosive and recorded by 26 three-component digital stations. The method used was based on the analysis of the spectral ratios, using the average spectrum calculated over 26 stations, as well as a «hard rock» station as the reference spectra. Spectral ratios appear to be broadly correlated with the geological characteristics of sites. A zonation of Benevento town with areas having a common shape of spectral ratio was obtained (fig. 12).

Though a significant number of seismic stations (26) were employed with respect to the area being investigated (about 16 km^2), the stations did not cover the various geological formations uniformely. Therefore, the seismic amplification map proposed here was obtained by extrapolating across areas with uniform geological conditions. Some areas, with distinct geological characteristics or not sampled by seismic stations, were not classified in the present paper. These areas are blank in fig. 12.

Although the zonation map proposed in fig. 12 was obtained analyzing a large set of data, it represents a first step in the estimation of the site response in the town of Benevento. This estimation performed with a specific technique will be compared with those obtained by applying other experimental and numerical simulation techniques. By comparing several methodologies it will be possible to prepare a microzonation map of the town of Benevento.

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