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Seismic Ground Motion in Napoli for the 1980 Irpinia Earthquake

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Abstract—The seismic ground motion in the urban area of Napoli has been computed for the 1980 earthquake (M_s = 6.9) with a hybrid technique based on the mode summation and the finite difference methods. The detailed geological setting of each quarter has been reconstructed from several stratigraphies and six geological zones have been recognized. Shear-wave velocity profiles have been assigned, based on hole tests and inversion of Rayleigh group velocities artificially generated.

Realistic *SH* and *P-SV* wave seismograms have been computed along the representative cross sections of each zone, by assuming selected velocity profiles. Spectral amplifications of 2–4 have been computed at frequencies roughly corresponding to the eigenfrequencies of the most damaged buildings. Moreover, following the intensity-PGA correlations found for the Italian territory, the predicted peak ground accelerations, 0.04–0.10 g correspond to the intensity range VII-VIII on the MCS scale, in agreement with the observed data.

Key words: Napoli, Irpinia earthquake 1980, synthetic seismograms, spectral amplification.

1. Introduction

Napoli is a good example of a large Mediterranean city with high seismic risk, mostly because of the high vulnerability due to the high density of population and the nature of the built environment. On the other hand, the seismic hazard is strictly dependent on the seismic amplification of the complex geological setting, with volcanic products erupted by different vents, and altered by weathering and rill-wash processes. In addition, during recent centuries the streams from the surrounding hills have been drained and filled with heterogeneous materials; often waste, and cavities have been artificially generated to extract tuff, extensively used as building stone.

Vulnerability may be reduced through the adequate retrofitting of ancient buildings and monuments as well as through the design of new reinforced structures which better resist the earthquake loads. Sound anti-seismic construction requires the knowledge of a correct seismic site response, both in terms of peak ground acceleration and response spectral content, based on methods which take into account source, travel path and local, well-defined soil conditions.

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Based on the historical records, the largest experienced intensity in Napoli is VIII on the MCS scale (ESPOSITO *et al.*, 1992). The 1980, Irpinia earthquake ($M_S = 6.9$, $M_L = 6.5$) is representative of a strong shaking in Napoli since it caused intensity VII on the MSK scale (POSTPISCHL *et al.*, 1985), roughly equivalent to intensity VIII (MCS). The damage was concentrated in the historical center and in the eastern area, and was verified through more than 20,000 stability essays on buildings (Fig. 1).

A lower level of damage was expected in Napoli since moderate peak ground accelerations of 0.06 g and 0.04 g, with dominant frequencies 2.5 and 3 Hz, were recorded along the north-south and east-west directions at the seismic station Torre del Greco, about 10 km east of Napoli located on a lava flow on the flanks of Vesuvius (Fig. 2). The recorded seismograms at Torre del Greco, the only instrumental recording of ground acceleration close to Napoli, have been reasonably

Legend

Very high Damage	**High Damage**	**Medium damage**	**Low damage**	**Available data unreliable**
11. Montecalvario	4. Chiaia	2. Bagnoli	1. Arenella	9. Miano
19. Poggioreale	5. S. Ferdinando	7. Chiaiano	3. Barra	14. Pendino
20. S. Lorenzo	10. Avvocata	16. Pianura	6. Posillipo	15. Mercato
21. Vicaria	12. S. Giuseppe	22. S. Pietro	8. Fuorigrotta	17. Piscinola
29. Zona Industriale	13. Porto		18. Ponticelli	24. Secondigliano
	26. Stella		23. S. Giovanni	30. Scampia
	27. S. Carlo		25. Soccavo	
			28. Vomero	

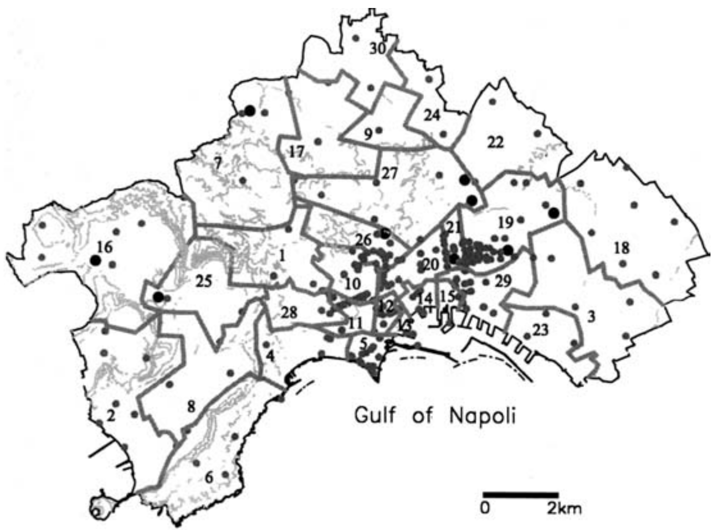

Figure 1
Urban map with quarter limits of Napoli (arabic numbers) and damage caused by the 1980 Irpinia earthquake. Location of drillings (grey dots) and FTAN measurement sites (black dots) is also shown.

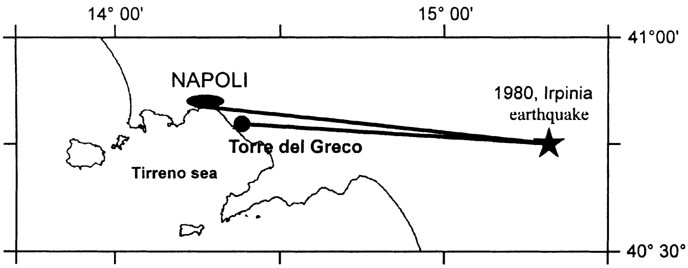

Figure 2
Location of epicenter of Irpinia 1980 earthquake, Torre del Greco (seismic station) and Napoli.

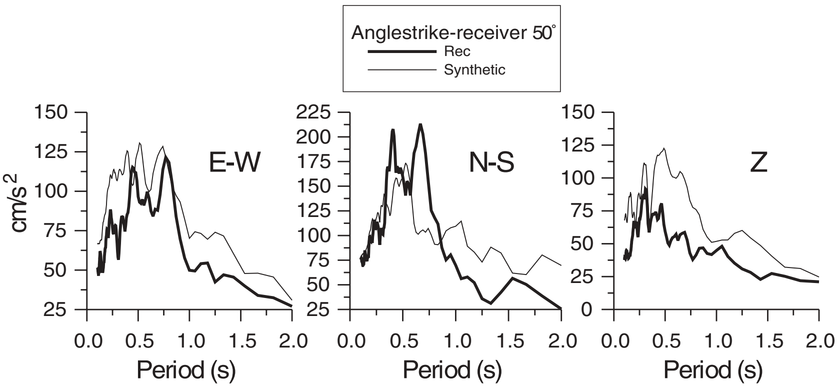

Figure 3
Comparison between synthetic and recorded response spectra, computed for a source-receiver backazimuth of 50°, at Torre del Greco accelerometer station (from NUNZIATA *et al.*, 2000).

fitted by synthetic seismograms (NUNZIATA *et al.*, 2000) computed with the mode summation technique (PANZA, 1985; FLORSCH *et al.*, 1991) (Fig. 3).

This validation and the availability of detailed geotechnical information pertaining to the local soil conditions allowed us to compute quite realistic ground motion at two areas of Napoli (Fig. 1): S. Lorenzo quarter, representative of the historical center (NUNZIATA *et al.*, 2002) and Centro Direzionale, within the quarter of Poggioreale, a newly developed area with skyscrapers of important social use (NUNZIATA *et al.*, 2000). Synthetic seismograms were computed by using the hybrid approach developed by FÄH (1992) which is based on the mode summation and the finite difference methods.

The aim of this paper is to estimate the seismic ground motion in Napoli for the 1980 Irpinia earthquake, based on the reconstruction, quarter by quarter of the geological, geotechnical and geophysical setting. Realistic *SH* and *P-SV* wave seismograms with complete body and surface waves are computed with the hybrid method developed by FÄH (1992) along representative geological cross sections, by assuming selected velocity profiles to test the sensitivity of the spectral amplification.

Then, average and maximum spectral amplifications and acceleration response spectra are considered for seismic risk mitigation.

2. Numerical Modelling of Seismic Ground Motion

The 1980 Irpinia earthquake ($M_S = 6.9$, $M_L = 6.5$) is the first strong event recorded close to Napoli at the seismic station Torre del Greco (Fig. 2).

The recorded seismograms at Torre del Greco have been used to calibrate synthetic seismograms computed with the mode summation technique (PANZA, 1985; FLORSCH *et al.*, 1991). The average reference model given by VACCARI *et al.* (1990) has been assumed for the propagation of the wavefield from the epicenter to Torre del Greco station and the source mechanism has been chosen accordingly with the main shock (0 s subevent) of the 1980 Irpinia earthquake: dip 65°, rake 270°, strike 315° (PANTOSTI and VALENSISE, 1993). Synthetic seismograms have been properly scaled to a finite dimension source according to the magnitude $M_s = 6.9$ of the Irpinia earthquake, by using the moment-magnitude relation given by KANAMORI (1977) (from which a seismic moment of 2.5×10^{19} Nm is computed) and the spectral scaling law proposed by GUSEV (1983) as reported in AKI (1987). Reasonable agreement between synthetic and observed response spectra (Fig. 3) has been obtained for a source-receiver back azimuth of 50° and a source depth of 7.0 km (NUNZIATA *et al.*, 2000).

This validation at hand and the availability of detailed geotechnical information concerning the local soil conditions has allowed us to compute quite realistic ground motion in Napoli by using the hybrid approach developed by FÄH (1992). The propagation of the waves from the source to the complex laterally varying structure is computed with the mode summation technique (PANZA, 1985; FLORSCH *et al.*, 1991), and in the laterally heterogeneous structure it is computed with the finite-difference method. A schematic representation of the hybrid method is shown in Figure 15. The path from the source to the laterally varying region is represented by a layered anelastic structure. The causative fault of the main shock of the 1980 earthquake is located approximately 90–100 km from Napoli. The angle between the strike of the fault and the epicenter cross section lines is 50°.

3. Geological Setting of Napoli

The geological setting of Napoli has been reconstructed from numerous geotechnical and stratigraphic data (AA.VV., 1967; Comune di Napoli, 1994) (Fig. 1). It is mainly characterized by pyroclastic materials, soil (pozzolana) and rock (tuff), from Campi Flegrei different eruptive centers and Vesuvius, that often underwent morphological changes due to the influence of the meteoric and marine agents and the urban settlement. The original material that forms the tuffs and the volcanic soil is in general the same, with the volcaniclastic rocks being the result of the hardening of the volcaniclastic soil by post-depositional hydrothermal alteration. Such hardening is not homogeneous so that welded facies may vanish and the tufaceous formation becomes incoherent, especially at the borders or where such bodies taper. Neapolitan soil includes sand along the coast, and alternations of volcanic soil, alluvial soil and organic materials.

Laboratory measurements of physical properties of several specimens extracted from drillings and quarries (AA.VV., 1967; VINALE, 1988; COMUNE DI NAPOLI, 1994; NUNZIATA *et al.*, 1999), show that Neapolitan soil generally ranges from silty sand to sandy silt.

The most widespread products belong to the Neapolitan Yellow Tuff (NYT) eruption (12,000 years), pozzolana and tuff, and the recent eruptions (< 12,000 years), essentially pozzolana. The tuff horizon also consists of ancient tuffs (Ignimbrite, Campi Flegrei and Vesuvius tuffs older than 15,000 years) in the northern and eastern part of Napoli. The tuff horizon is on average at 10–30 m of depth, but deepens to more than 90 m in the western area and more than 40 m in the southeastern area of Napoli. The compact tuff horizon represents the Neapolitan seismic bedrock with $V_s > 750$ m/s (NUNZIATA *et al.*, this issue).

Taking into account the stratigraphies, six geologically homogeneous zones can be recognized in Napoli (Fig. 4).

Zone 1—Zone 1 is comprehensive of the quarters of Fuorigrotta, Bagnoli, Soccavo and Pianura, in the western part of Napoli (Fig. 1). The analysis of many

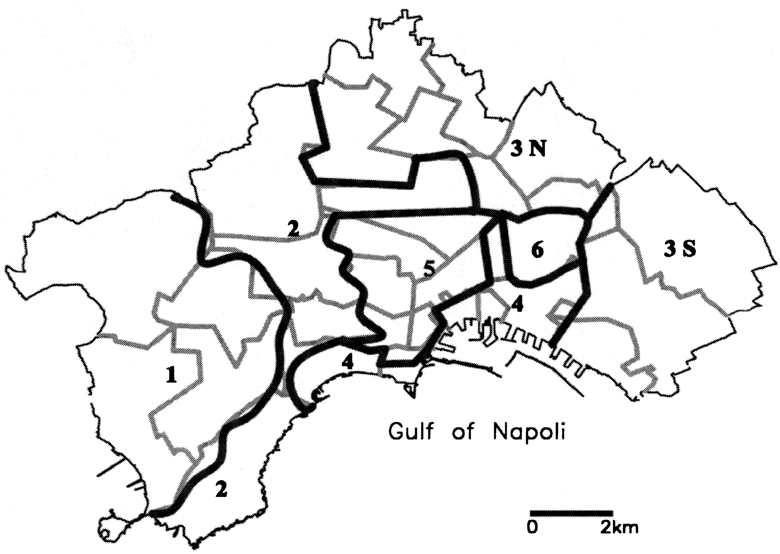

Figure 4
Map of the homogeneous geological zones of Napoli (black lines). The limits of the quarters are also shown (grey lines).

stratigraphies points out that the area is quite homogeneous, being characterized by a thick cover (more than one hundred meters) of recent pyroclastic products (< 12,000 years) on marine sand or occasionally, Neapolitan Yellow Tuff formation.

Zone 2—Zone 2 is comprehensive of the quarters of Chiaiano, S. Carlo, Arenella, Vomero and Posillipo (Fig. 1). It is characterized by the presence of recent pyroclastic products and man-made materials on Neapolitan Yellow Tuff (NYT) formation, both soil and lithoid facies. The NYT tuff horizon is generally 15 m deep from the ground surface, and sporadically very shallow (< 5 m) or deeper than 20 m.

Zone 3—Zone 3 is located on the eastern side of Napoli and has been divided into a northern part, zone 3N, and a southern part, zone 3S. Zone 3N includes the quarters of Piscinola, Miano, Secondigliano, Scampia, S. Pietro, part of Poggioreale, while Ponticelli, Barra, and S. Giovanni belong to zone 3S (Fig. 1). It is characterized by the presence of ancient tuff horizon at about 40 m of depth. A cover of NYT pozzolana and Campanian Ignimbrite products characterizes zone 3N, and of Vesuvius tuff, both soil and lithoid facies, zone 3S.

Zone 4—In the recent past this area was under sea level. As a consequence, the representative stratigraphic soil column consists of marine sand on NYT formation, both soil and lithoid facies. NYT tuff horizon is generally at 30 m of depth, and deepens on the southeastern side of Napoli. It comprehends the quarters of Chiaia, the southern part of S. Ferdinando, the southern part of Porto, Mercato, Pendino, Vicaria, and Zona Industriale (Fig. 1).

Zone 5—This zone includes the historical center of Napoli, that is the quarters of S. Lorenzo, Avvocata, Montecalvario, S. Giuseppe, Stella, and the southern part of S. Carlo (Fig. 1). The main peculiarity is the presence of several cavities in the tuff formation. The first excavations were tuff quarries and aqueducts and are dated VIII century B. C. Tuff was extracted to be used as a building stone and, preferably, in the same place. Thus it commonly happened that a building was built with tuff stones extracted below it. The shallow geological setting has been complicated by huge, natural and artificial, morphological changes, as for example the filling of river beds and hollows with alluvial materials and bricks. Hence the historical center of Napoli is characterized by a cover of man-made ground, up to 20 m of thickness, and pyroclastic soil (pozzolana) overlying a NYT tuff horizon with several cavities.

Zone 6—This zone comprehends the southern part of Poggioreale quarter (Fig. 1). Considerable geological, geotechnical and geophysical information is available for this area since Centro Direzionale with many skyscrapers has been built here after the 1980 earthquake. The area was a marsh recently drained both for urban development and for the reduction of the water supply. Water channels were later filled with bricks and waste materials. The sub-soil, affected by significant lateral variations, is mainly formed by man-made ground, alluvial soil (ash, sand, peat), loose and slightly cemented pozzolanas, NYT tuff and marine sand. It is a flat area about 10 m above sea level with the water table a few meters deep (NUNZIATA *et al.*, 2000).

4. Spectral Amplification

Sophisticated computing techniques such as finite difference can be applied if detailed geometries and seismic parameters, mostly shear-wave velocities V_s, are available. Several measurements of V_s have been made in Napoli by down- and cross-hole tests (COMUNE DI NAPOLI, 1994; VINALE, 1988). The analysis of such measurements, together with the geological and geotechnical characteristics of the investigated soils, has evidenced a wide scattering of V_s velocities, even for the same formation, mostly due to the textural characteristics and the different hardening degrees, and to the influence of the vertical pressure, for the incoherent deposits (NUNZIATA *et al.*, 1999; this issue). Frequently, strong variations of velocities have been reported in the DH-CH velocity profiles at a local scale (within 1 m), explainable both in terms of arrival time picking errors and of the pumiceous and lapilli content of the Neapolitan pyroclastic soil. Then, V_s database was implemented with measurements in representative lithostratigraphic sites of Napoli obtained from the inversion, with the Hedgehog method (VALYUS *et al.*, 1968; PANZA, 1981), of the group velocity dispersion curve of the fundamental mode of Rayleigh waves, artificially generated. Such dispersion curve is extracted from a signal recorded in refraction seismic surveys, employing the FTAN method on single channels (LEVSHIN *et al.*, 1992). FTAN-Hedgehog V_s models represent average values over distances of 50–100 m and are more suitable than DH-CH point measurements for seismic response analysis. Beside this, the good agreement of FTAN-Hedgehog with cross-hole measurements, has allowed us to enrich the database and to acquire experience enough to select for each zone (Fig. 4) some V_s models for the evaluation of the spectral amplification. Shear quality factors Q_s have been attributed on the basis of laboratory measurements of damping (GUADAGNO *et al.*, 1992; VINALE, 1988), and compression quality factors Q_p have been computed as 2.5 Q_s.

Site amplification effects have been estimated in terms of spectral amplification and defined as the response spectrum at a site in the 2-D structural model, normalized to the response spectrum computed for the 1-D average reference model (VACCARI *et al.*, 1990). For the computation of the response spectra 2% and 5% dampings have been assumed, respectively, for masonry structures and reinforced concrete buildings.

In the following, V_s models and computed spectral amplifications are presented zone by zone.

4.1 Zone 1

About 20 down- and cross-hole tests (COMUNE DI NAPOLI, 1994) and 2 V_s velocity profiles from FTAN-Hedgehog measurements (NUNZIATA *et al.*, this issue) have been collected for Zone 1. A wide ranging variability of V_s velocities has resulted, even if the stratigraphy is laterally homogeneous and it consists of recent pyroclastic soil.

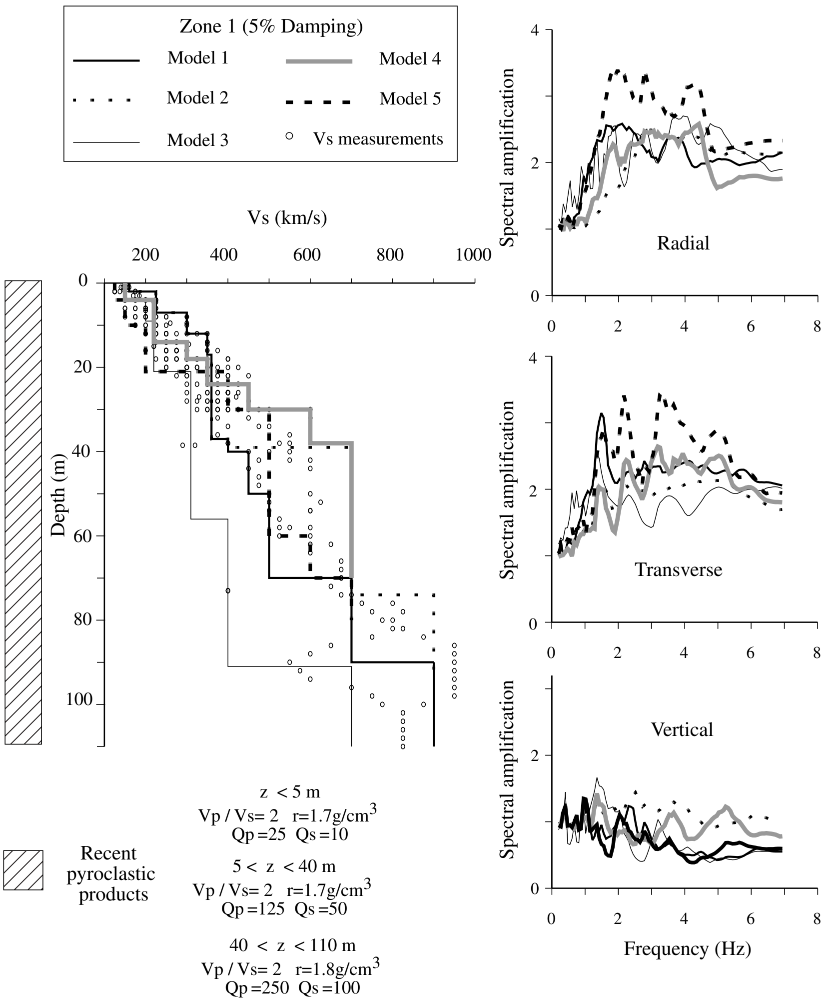

Figure 5
Representative stratigraphic column and V_s measurements (circles) at zone 1 (see Fig. 4 for location). A suite of 5 possible V_s models has been selected (lines) for which spectral amplifications for the *SH* and *P-SV* wave components have been computed.

Five different velocity profiles have been selected as being representative of the zone 1 (Fig. 5) to study their effect on the spectral amplification. In particular, models 1 and 3 are the average V_s profiles which were obtained from FTAN-Hedgehog measurements at Pianura and Soccavo quarters, respectively (see Fig. 1 for quarter location). Model 2 differs from model 1 at depths greater than 40 m, and can be considered as the envelope of the highest measured velocities. Models 4 and 5 are 2-DH velocity profiles and have been considered as a representation of the lowest and average shear velocities in the uppermost 20 m of subsoil. Model 1 is representative of Pianura and Fuorigrotta, model 3 refers to Soccavo quarter, and models 4 and 5 are representative of Bagnoli quarter (Figs. 5 and 1).

Spectral amplifications have been computed for 5% damping, as the majority of houses, typically 5–7 floors, roughly corresponding to 1.5–2 Hz eigenfrequencies, have been built after 1950. They are similar along radial and transverse components and double that along vertical components (Fig. 5). Horizontal amplifications are about 2–3, and more than 3 for the V_s model 5. Transverse spectral amplifications show the same relative maximum peaks at about 1.5, 2.5 and 3.5 Hz with different amplitudes for the different V_s models. Average and maximum spectral amplifications have been computed for practical use (Fig. 6). The peak of the horizontal spectral amplification around 2 Hz is in correspondence with the building eigenfrequencies.

Average and maximum peak ground accelerations (PGA) of 0.04–0.05 g have been computed in the horizontal plane. Following the intensity-PGA correlations found for the Italian territory (PANZA *et al.*, 1999), predicted average peak ground accelerations correspond to the intensity range VII–VIII on the MCS scale, in agreement with the observed data. Concluding, average and maximum response spectra have been computed and are characterized in the horizontal plane by accelerations of 0.1–0.2 g in the 0.2–0.8 s period range (Fig. 6). A possible explanation of the different damage levels caused by the 1980 earthquake (Fig. 1) can be found in the prevailing presence of concrete buildings (70%) at Soccavo and Fuorigrotta quarters (low damage in Fig. 1), and of masonry structures (70%) at Bagnoli and Pianura (medium damage in Fig. 1). The sparse information regarding damage and floor number of buildings (RIPPA *et al.*, 1983) indicates more extensive damage for 6–7 floor concrete buildings at Bagnoli and Fuorigrotta quarters, which is in agreement with the peak of the spectral amplification at about 1.5 Hz (Fig. 6).

4.2 Zone 2

The 1980 earthquake caused minor damage at the quarters of Arenella, Vomero and Posillipo, medium and major damage at Chiaiano and S. Carlo quarters, respectively (Fig. 1). Tall concrete buildings prevail at Arenella quarter ($>$ 5 floors) and are abundant in the northern area of S. Carlo quarter, at Vomero and Posillipo quarters. Instead masonry buildings (mostly 4–6 floors) are abundant at Chiaiano quarter and in the southern part of S.Carlo quarter.

Taking into account all down- and cross-hole V_s measurements, three V_s models can be assumed as representative of the different stratigraphic typologies (Fig. 7). Models 1 and 2 are referred to sites with very shallow NYT tuff horizon (statigraphy A), while model 3 also must be considered at typical stratigraphy B (average NYT tuff depth of 15 m) and sporadic stratigraphy C (NYT tuff depth of about 30 m). The selected V_s models have been used to compute spectral amplifications for 2% damping along plane-parallel cross sections (Fig. 8). As expected, V_s model 1 does not amplify. V_s model 2 is responsible for similar amplifications along radial and

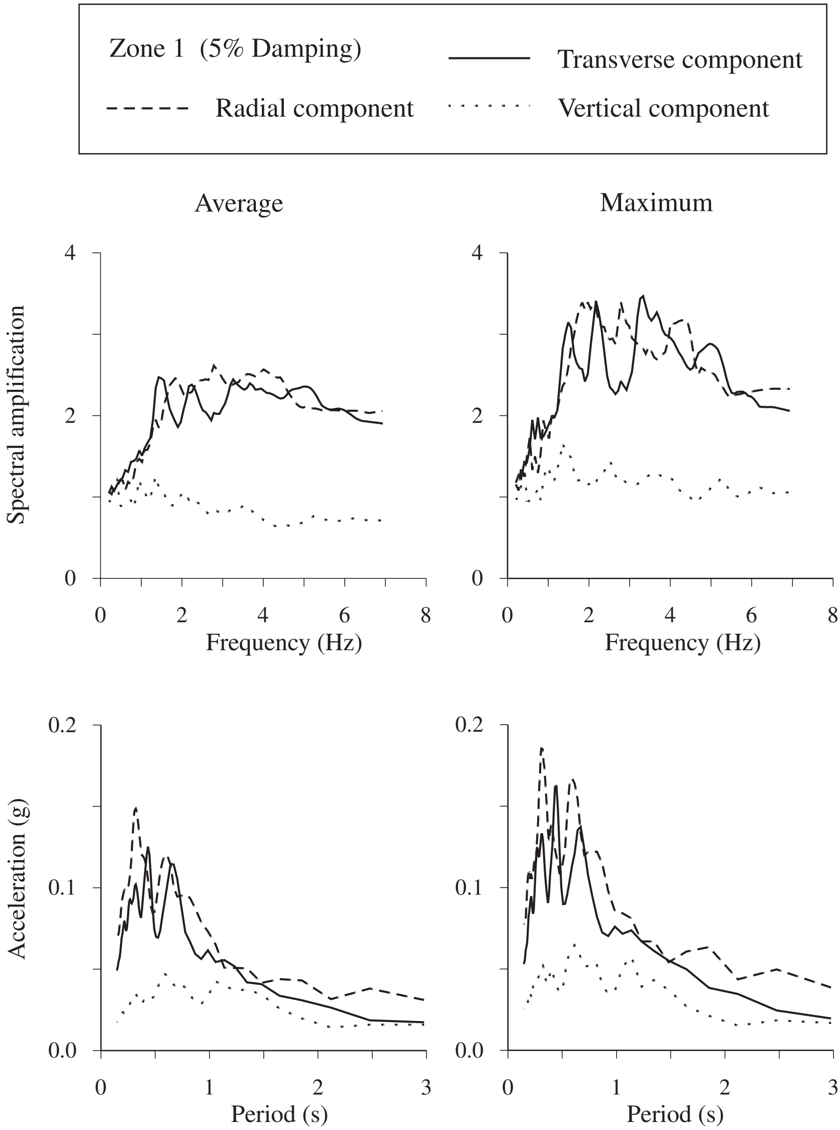

Figure 6
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 1 (see Fig. 4 for location).

transverse components of the ground motion, that is about 2 at 3.5–6 Hz frequency range. Spectral amplification computed for the V_s model 3 has a peak of 2–3 at 2–3 Hz, in the horizontal plane, and another peak at about 6 Hz along the radial component. Spectral amplification along the vertical component is negligible, except for the V_s model 3.

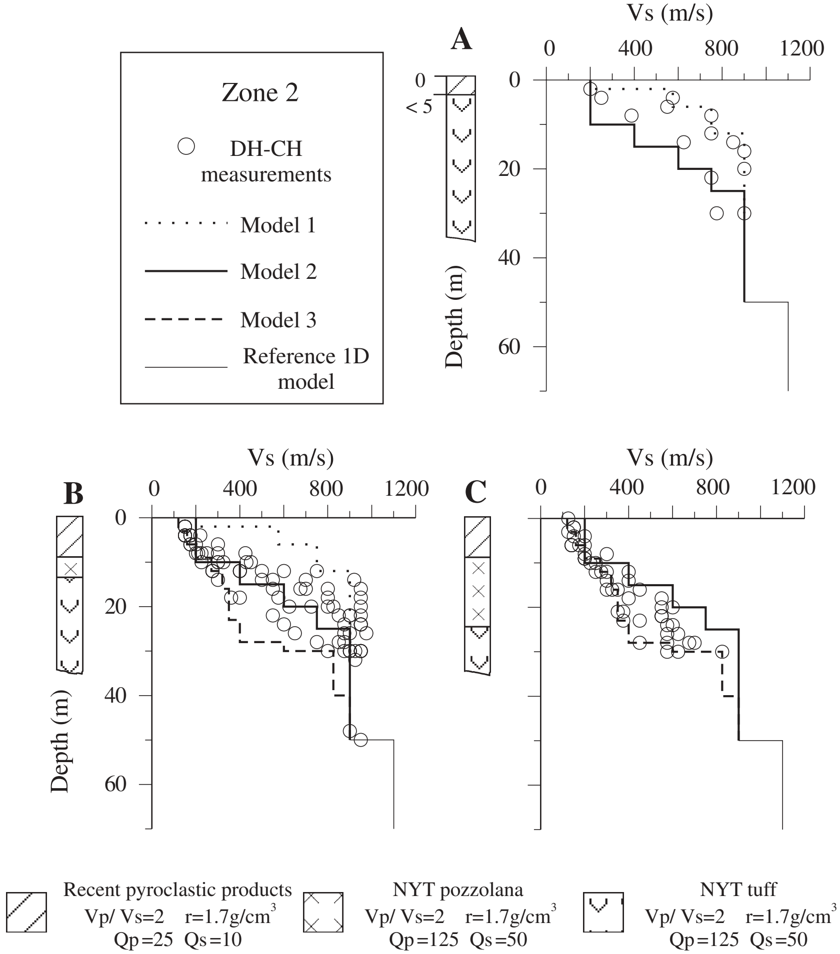

Figure 7
Representative stratigraphic columns and V_s measurements (circles) at zone 2 (see Fig. 4 for location). A suite of 3 possible V_s models has been selected (lines).

The horizontal spectral amplifications are consistent with the observed damage: low amplifications have been computed at low frequency (< 1.5 Hz), corresponding to the average building typology at Arenella, Vomero and Posillipo quarters; high peaks of amplifications have been computed corresponding to the eigenfrequencies of 4 floor buildings on soil with V_s model 3 and 1–2 floor buildings on soil with V_s model 2. The amplification at 2–3 Hz corresponds to the eigenfrequencies of buildings with medium and high damage. Since the chosen V_s models are more or less present at each quarter, average and maximum spectral amplifications have been assumed as being representative of the zone 2 (Fig. 9).

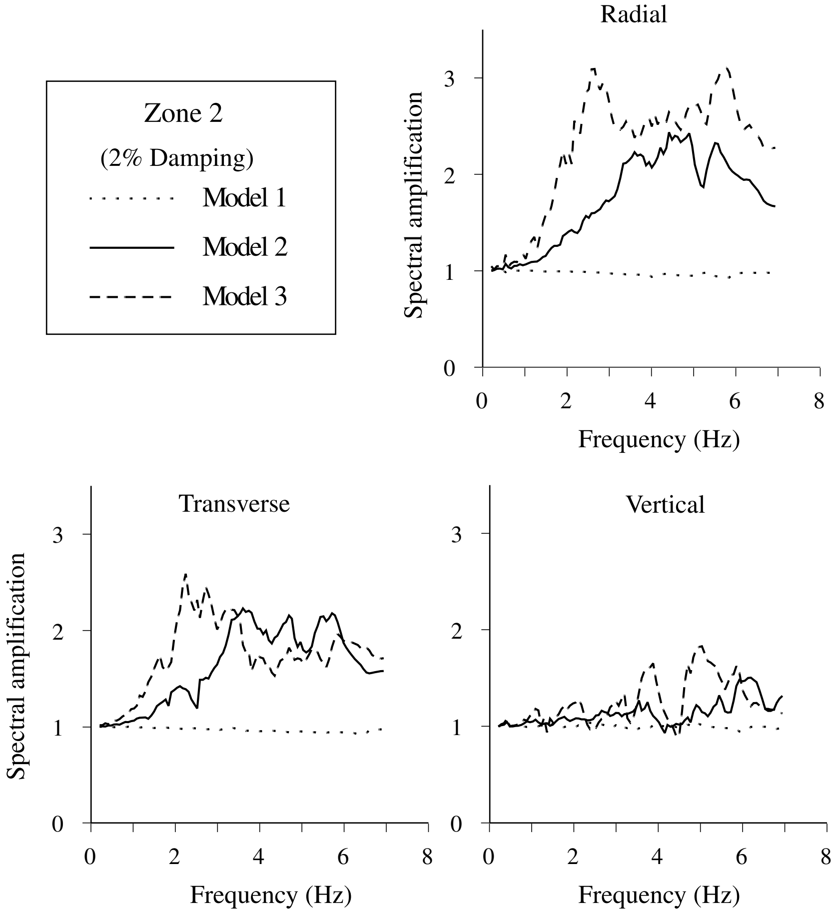

Figure 8
Spectral amplifications computed for the *SH* and *P-SV* wave components at zone 2 (see Fig. 4 for location) for the selected V_s models in Figure 7.

Response spectra have then been computed (Fig. 9). Average and maximum PGA of 0.04–0.06 g and 0.03–0.04 g, respectively along radial and transverse components of the ground motion, have been computed and, following the intensity-PGA correlation (PANZA *et al.*, 1999), correspond to I = VII–VIII on the MCS scale, being VIII relatively to V_s model 3.

4.3 Zone 3

DH and CH measurements have been collected and FTAN measurements have been carried out at three sites of zone 3 (Figs. 1 and 4). As regards the northern area, zone 3N, 4 V_s models have been taken into consideration (Fig. 10). Models 1 to 3 are the average Hedgehog solutions of the inversion of FTAN measurements, and model

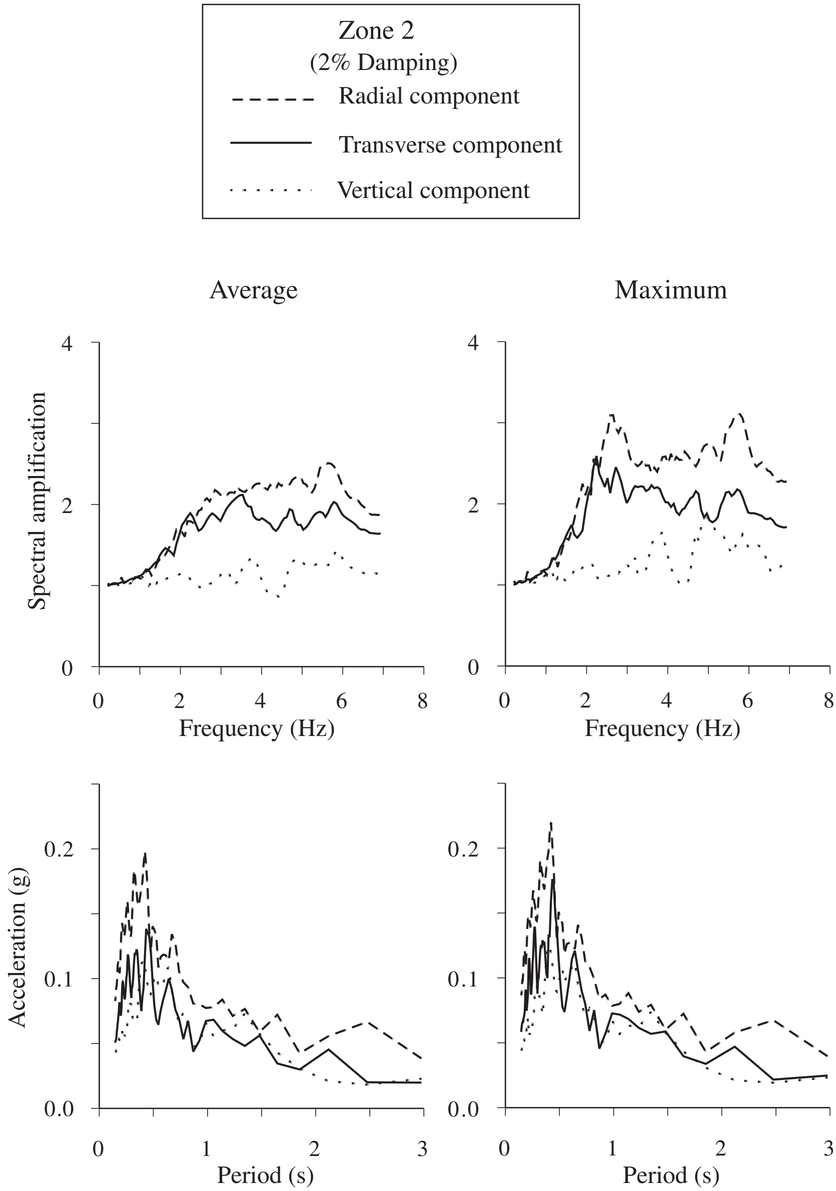

Figure 9
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 2 (see Fig. 4 for location).

4 represents an average V_s profile based on DH-CH measurements for the representative geological cross section. In particular, model 3 has been obtained at the site where a 8-floor building collapsed in the 1980 earthquake. Spectral

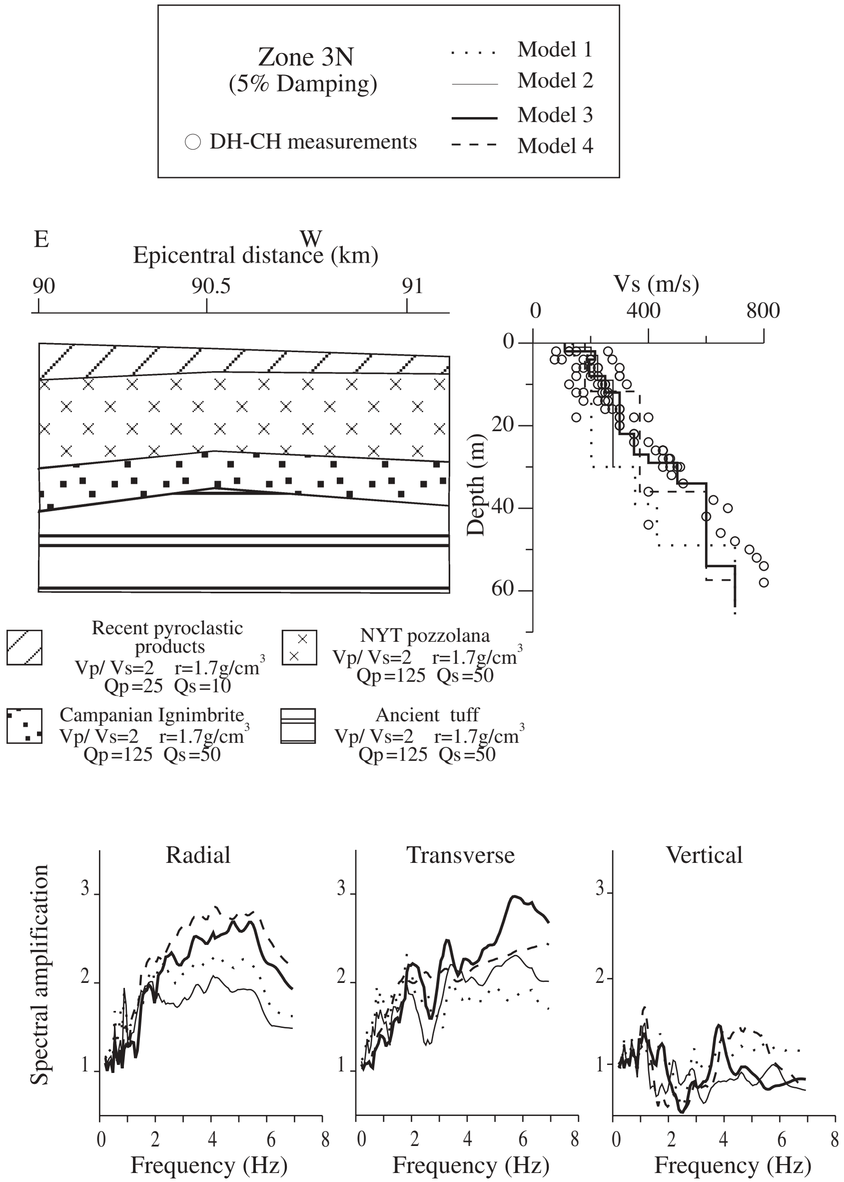

Figure 10
Geological cross section representative of zone 3N (see Fig. 4 for location) and physical parameters of the soil. Spectral amplifications have been computed for the *SH* and *P-SV* wave components for the selected V_s models.

amplification has been computed for the different V_s models by assuming 5% damping, due to the building typology. The only information about dependence of damage on number of floors regards the quarter of Secondigliano (Fig. 1) and reports that the most damaged buildings had 5–6 floors (RIPPA and VINALE, 1983). Radial and transverse spectral amplifications exhibit similar features for the different V_s models, that is values between 2 and 3 at 2–7 Hz frequency range. The relative maximum peak at 2 Hz corresponds to the eigenfrequencies of the most damaged buildings. A negligible amplification has resulted at about 1 Hz, roughly corresponding to the eigenfrequency of the collapsed building (T $\sim$ 0.8 s).

As regards the southern area of zone 3, zone 3S (Fig. 4), 2 V_s models have been assigned, based on lower and higher DH-CH measurements (Fig. 11). Average radial and transverse spectral amplifications show relative maximum peaks of about 2 at 3–6 Hz and 2–7 Hz frequency range, respectively, and they are similar to those computed at zone 3N. Spectral amplification along the vertical component is negligible at zone 3. The only data of correlation between damage and number of floors are relative to the quarter of Barra and indicate that the most damaged buildings were 4–8 floors high (RIPPA and VINALE, 1983). Only 4 floor buildings (about 2.5 Hz) have correspondence with peaks of spectral amplification. Average and maximum amplifications have been computed between zone 3N and zone 3S, and considered as representative of zone 3 (Fig. 12). Average and maximum response spectra also have been computed and they show a main peak at 0.3–0.5 s, and a second lower one at 0.5–0.7 s, close to the eigenperiods of the existing 6–8 floor buildings (Fig. 12). Peak ground accelerations of 0.05–0.07 g and 0.04–0.05 g have been computed along the radial and transverse components of the ground motion, respectively, corresponding to intensity range VII-VIII on the MCS scale.

4.4 Zone 4

Massive damage was caused by the 1980 earthquake at zone 4 (Fig. 1), characterized by old and ancient masonry houses (about 90%), generally with 4–6 floors. Velocity profiles of shear waves have been assigned, based on the analysis of the DH-CH measurements and a FTAN measurement. The resulting seismic and stratigraphic pattern is shown along a E-W cross section and can be considered as representative of zone 4 (Fig. 13). Water level is a few meters deep, below the layer of man-made ground material. V_s increases from 200 m/s to 400 m/s in the soil and reaches the value of 800 m/s in the compact NYT tuff. Lateral variations are quite smooth and the shape of the computed spectral amplifications changes only moderately along the cross section, except for the peak amplitudes. Thereafter, average and maximum spectral amplifications have been computed for 2% damping and they manifest similar features in the horizontal plane (Fig. 14), with a main peak of about 3 at 2 Hz. Instead, vertical amplification is negligible.

Data of correlations between floor numbers and damage percentage at Chiaia, S. Ferdinando and Pendino quarters (Fig. 1) have indicated a broad interval of severest damage between 2 and 6 floor buildings (RIPPA and VINALE, 1983). These

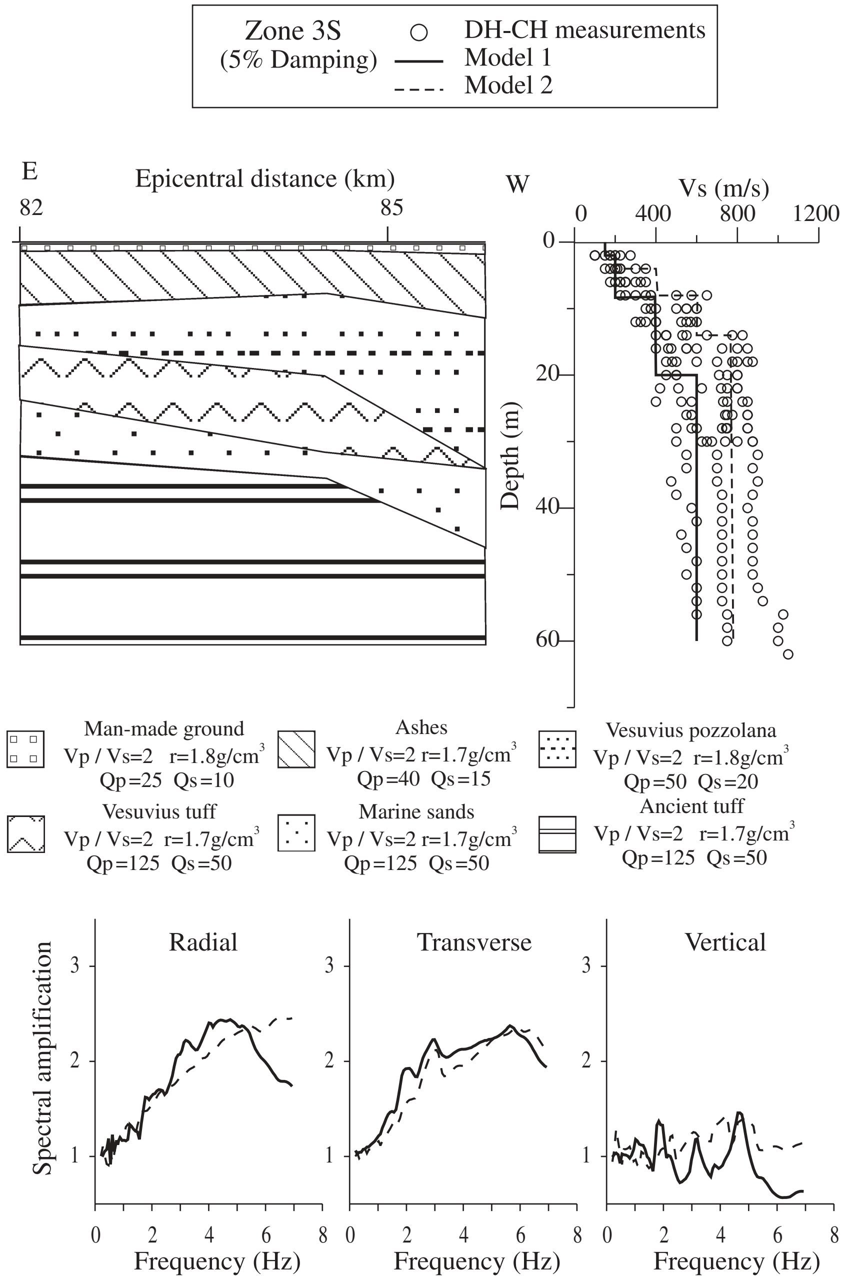

Figure 11

Geological cross section representative of zone 3S (see Fig. 4 for location) and physical parameters of the soil. Spectral amplifications have been computed for the *SH* and *P-SV* wave components for the selected V_s models.

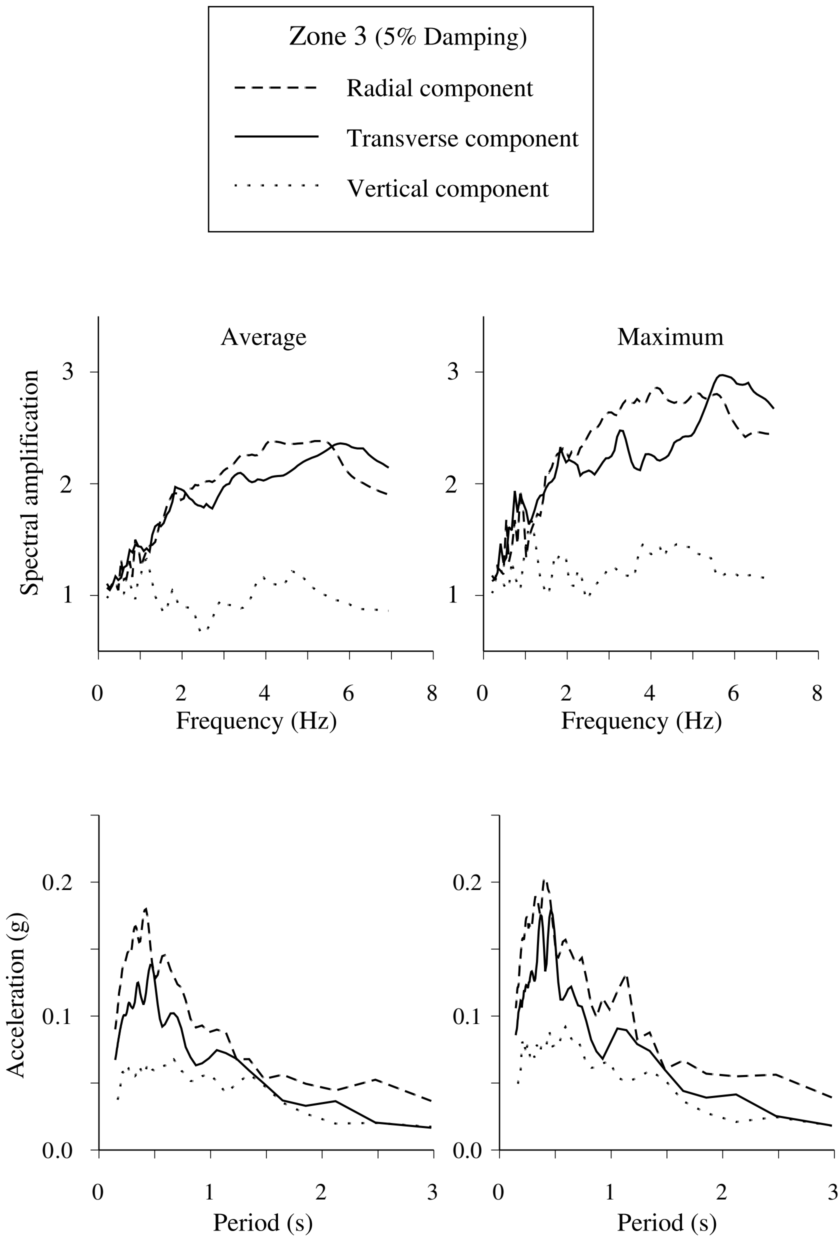

Figure 12
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 3 (see Fig. 4 for location).

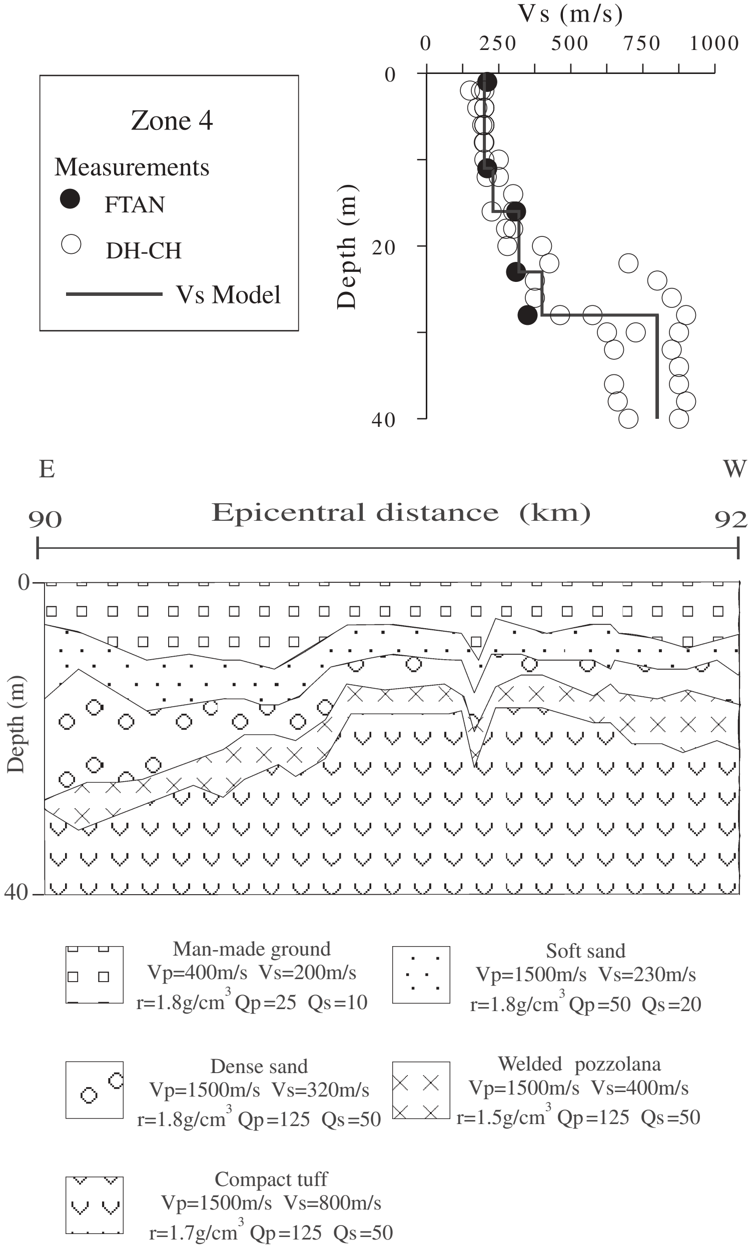

Figure 13
Geological cross section representative of zone 4 (see Fig. 4 for location) and physical parameters of the soil. The selected V_s model is shown at the top.

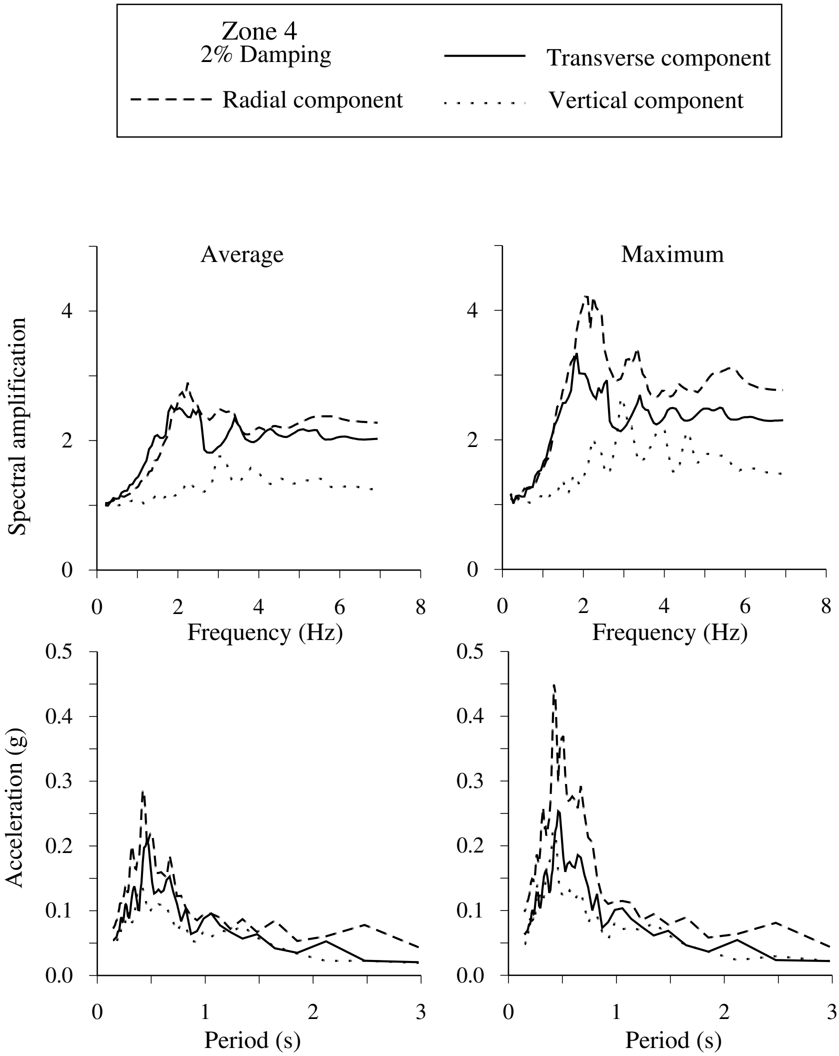

Figure 14
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 4 (see Fig. 4 for location), along the cross section shown in Figure 13.

data are in a good agreement with the peaks of the computed spectral amplifications. Computed average and maximum response spectra show horizontal maximum accelerations from 0.2 g to about 0.4 g at 0.4–0.6 s (Fig. 14). Average and maximum PGA of 0.04–0.05 g and 0.06–0.07 g, have been computed along transverse and radial components, respectively, and they correspond to about VIII intensity on the MCS scale (PANZA *et al.*, 1999).

4.5 Zone 5

Increasingly severe damage was reported at zone 5, characterized by ancient and old buildings of typically 3–6 floors.

Recently, NUNZIATA *et al.* (2002) computed the effect of the numerous cavities in the area, geometrically well-defined, on the SH-wave ground motion. In particular, it was evidenced that the presence of cavities in the tuff horizon (1–18 m wide and 7–16 m deep) causes a small reduction of the peak ground acceleration whereas their spatial distribution is of approximately one hundred meters, otherwise there is no effect. V_s model, which had been attributed on DH-CH measurements (COMUNE DI NAPOLI,

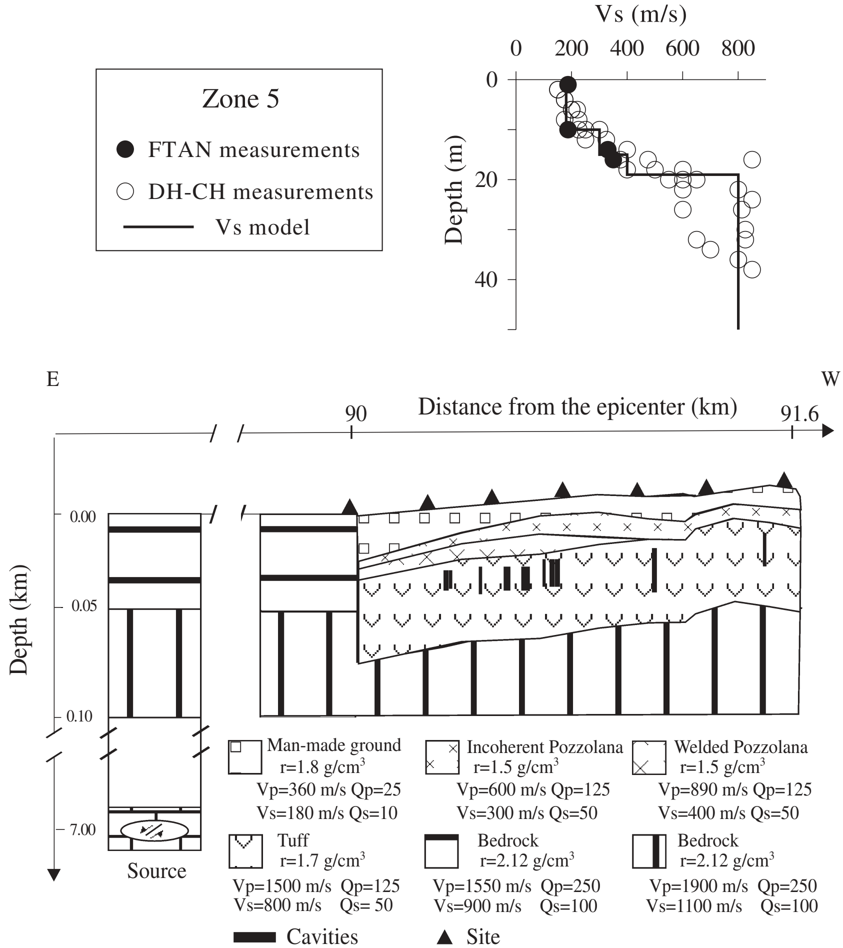

Figure 15

Geological cross-section representative of the historical center of Napoli (zone 5 in Fig. 4) and physical parameters of the soil. The selected V_s model is shown at the top. A schematic representation of the hybrid method is also shown.

1994), has been validated by recent FTAN measurements at Vicaria quarter (Figs. 15 and 1). Ground motion for *SH* and *P-SV* waves has been computed along the representative cross section (Fig. 15). Peak ground accelerations of 0.06–0.07 g and of 0.04–0.05 g have been computed along the radial and transverse components. These PGA values correspond to intensity VIII on the MCS scale (PANZA *et al.*, 1999). Average and maximum spectral amplifications, computed for 2% damping as more than 90% of buildings are masonry structures, are characterized by similar maximum peaks in the horizontal plane, which is between 2 and 4 at 2 Hz, with radial

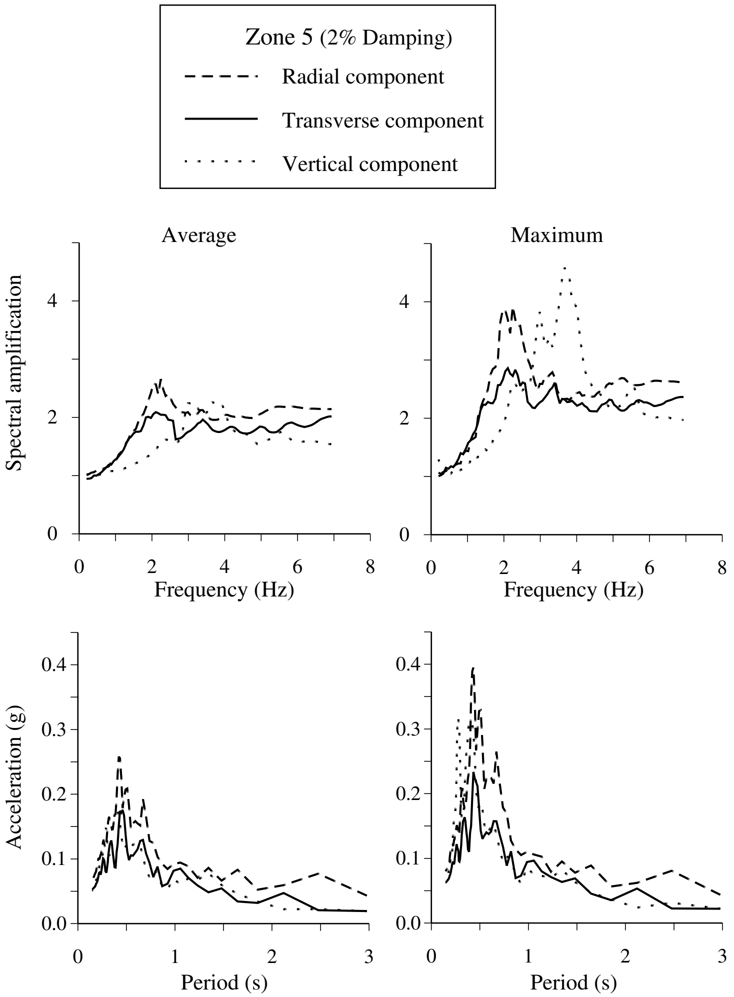

Figure 16
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 5 (see Fig. 4 for location), along the cross section shown in Figure 15.

amplification higher than the transverse one (Fig. 16). The maximum peak of the spectral amplifications is very close to the eigenfrequencies of the existing and most damaged buildings. As regards the vertical component, spectral amplification is characterized by a maximum peak of about 4 at 4 Hz. Finally, response spectra have been computed based on average and maximum spectral amplifications. The predominance of the radial component of the ground motion (Fig. 16) is even clearer.

4.6 Zone 6

Detailed knowledge of the stratigraphies and seismic velocity profiles already had been utilized to compute ground motion at zone 6 (Nunziata *et al.*, 1997; 2000). In particular, a parametric study was also done by considering different velocity profiles measured on very close sites. Ground motion modeling of complete *SH*- and *P-SV*-wave seismograms (Nunziata *et al.*, 2000) showed that the surficial soil deposits, which are composed of pyroclastic and alluvial materials with lateral discontinuities are responsible for an increase in amplitude of the radial and transverse components of the signal relative to the bedrock. Substantial variability of the ground motion resulted, mostly related to the presence of a discontinuous layer of peat with very low V_s values. In the light of the wide scattering of V_s velocities in the area, FTAN measurements have been carried out inside the zone. The obtained V_s models are characterized by similar ranges for ashes and sandy soil. Moreover, peat layers resemble the surrounding soils. The representative E-W cross section with geological and geophysical parameters is shown in Figure 17.

The unconsolidated sediments amplify of 2–4 some of the frequencies of the incoming wavetrain (Fig. 18). These frequencies range 1–2 Hz for the radial and transverse components, while the vertical component is negligibly amplified. Average and maximum spectral response spectra have been computed for 5% damping and they indicate that 7–10 floor buildings should face the highest horizontal accelerations. Concludingly, peak ground accelerations of 0.06–0.08 g and 0.08–0.10 g have been computed along the transverse and radial components, respectively. Taking into account the correlation obtained for the Italian territory between synthetic PGA on one side, and intensity on the other (Panza *et al.*, 1999), we might expect macroseismic intensities VIII (MCS).

5. *Conclusions*

The validation of synthetic seismograms with the instrumental recording at Torre del Greco station, together with the detailed study of stratigraphies and V_s profiles, has allowed us to model the ground motion in Napoli. Sound average and maximum spectral amplifications have been computed based on selected V_s models. They are characterized by peaks of 2–4 at frequencies close to the eigenfrequencies of the

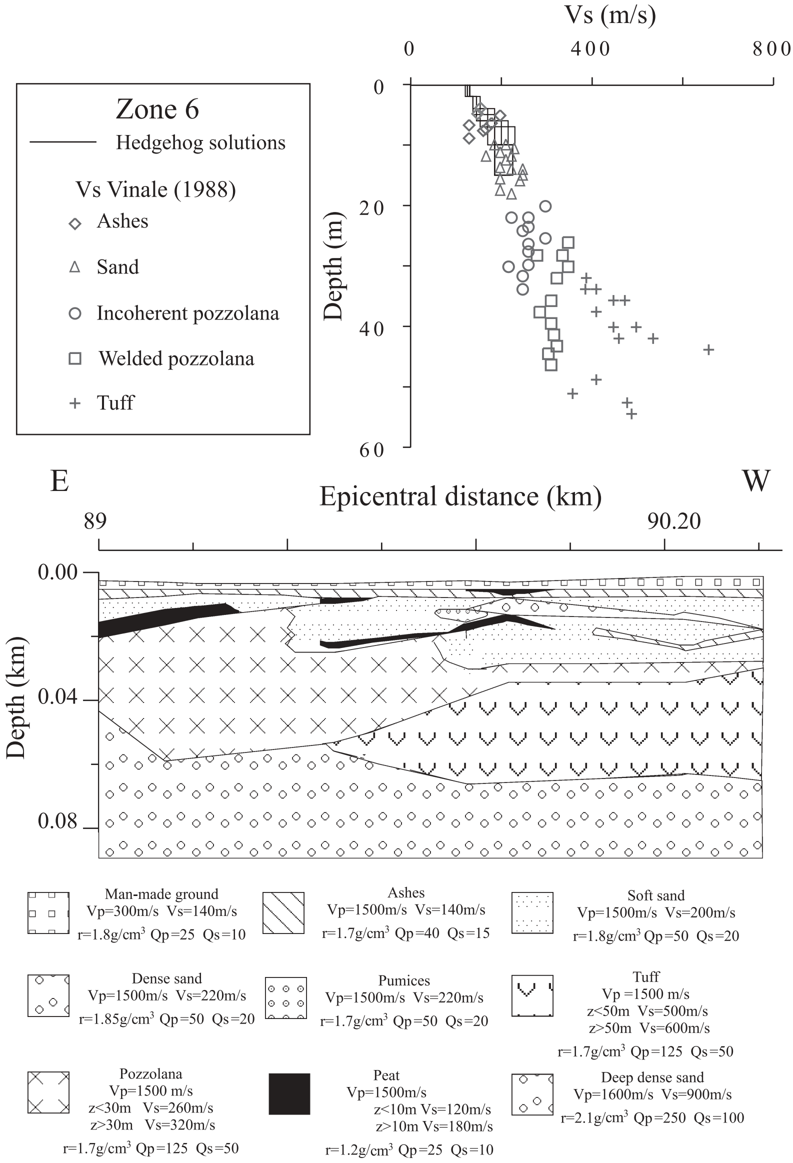

Figure 17

Geological cross section representative of the Centro Direzionale (zone 6 in Fig. 4) and physical parameters of the soil. V_s velocities have been assigned, based on measurements shown at the top.

damaged buildings, indicating that damage can be attributed not only to degradation of the buildings but also to site effects.

Following the correlation obtained for the Italian territory between synthetic PGA on one side, and intensity on the other (PANZA *et al.*, 1999), it resulted that the

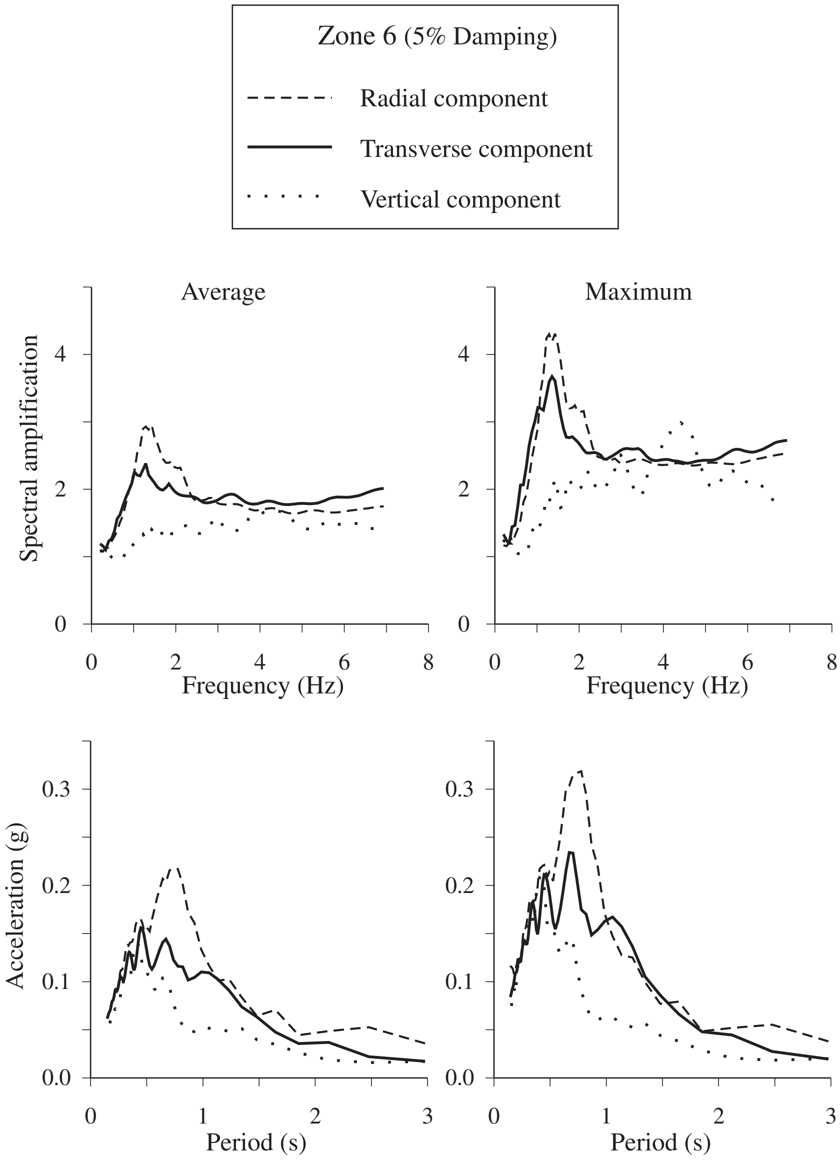

Figure 18
Average and maximum spectral amplifications and response spectra computed for the *SH* and *P-SV* wave components at zone 6 (see Fig. 4 for location), along the cross section shown in Figure 17.

zones with the highest intensity, VIII on the MCS scale, are the historical center (zone 5) and the Centro Direzionale (zone 6), followed by the zone 4, and then by all the other zones (I = VII–VIII MCS). Except for the Centro Direzionale, built after the 1980 earthquake, the computed intensities are in agreement with observed data.

Our results establish that a preventive definition of the seismic hazard in Napoli can be obtained immediately, without the need to wait for another strong event to occur, from the computation of time histories corresponding to possible seismotectonic scenarios for different sources and structural models. Then, the formulation of reliable building codes, based on the evaluation of the main potential earthquakes, will have a primary impact on the effective reduction of the seismic vulnerability of Napoli.

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