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Mitigation of seismic hazard of a megacity: the case of Naples

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Abstract

The seismic ground motion of a test area in the eastern district of Naples was computed with a hybrid technique based on the mode summation and the finite difference methods. This technique allowed the realistic modelling of source and propagation effects, including local soil conditions. In the modelling, as seismic source we considered the 1980 Irpinia earthquake, a good example of strong shaking for the area of Naples, located about 90 km from the source. Along a profile through Naples, trending N86°W, the subsoil is mainly formed by alluvial (ash, stratified sand and peat) and pyroclastic materials overlying a pyroclastic rock (yellow Neapolitan tuff) representing the Neapolitan bedrock. The detailed information available on the subsoil mechanical properties and its geometry warrants the application of the sophisticated hybrid technique. For *SH*-waves, a comparison was made between a realistic 2-D seismic response and a standard 1-D response, based on the vertical propagation of waves in a plane layered structure. As expected the sedimentary cover caused an increase in the signal's amplitudes and duration. If a thin uniform peat layer is present, the amplification effects are reduced, and the peak ground accelerations are similar to those observed for the bedrock model. This can be explained by the backscattering of wave energy at such a layer. The discrepancies evidenced between the 1-D and the 2-D seismic response suggest that serious caution must be taken in the formulation of seismic regulations. This is particularly true in the presence of the thin peat layer where the mismatch between the 1-D and the 2-D amplification functions is particularly evident in correspondence of the dominant peak and of the second significant peak.

Key words *seismic hazard – microzoning – numerical modelling – Naples*

1. Introduction

The main seismogenic areas of Southern Italy are located in the Southern Apennines. Naples is not within a seismogenic area, but it has often been severely damaged by Apennine earthquakes. The last strong event, the November 23, 1980 ($M_s = 6.9$, $M_L = 6.5$), Irpinia earthquake, produced serious damage in Naples (fig. 1), mostly in the historical centre and in the eastern area (Rippa and Vinale, 1983), despite the expected moderate ground shaking. In fact, peak ground accelerations of 0.06 g and 0.04 g, with dominant frequencies at 2.5 and 3 Hz, were recorded along the N-S and E-W directions at the seismic station Torre del Greco. This station is located on a lava deposit on the Vesuvius flanks, about 20 km from Naples, on a similar azimuth from the epicenter. Due to the larger epicentral distance of

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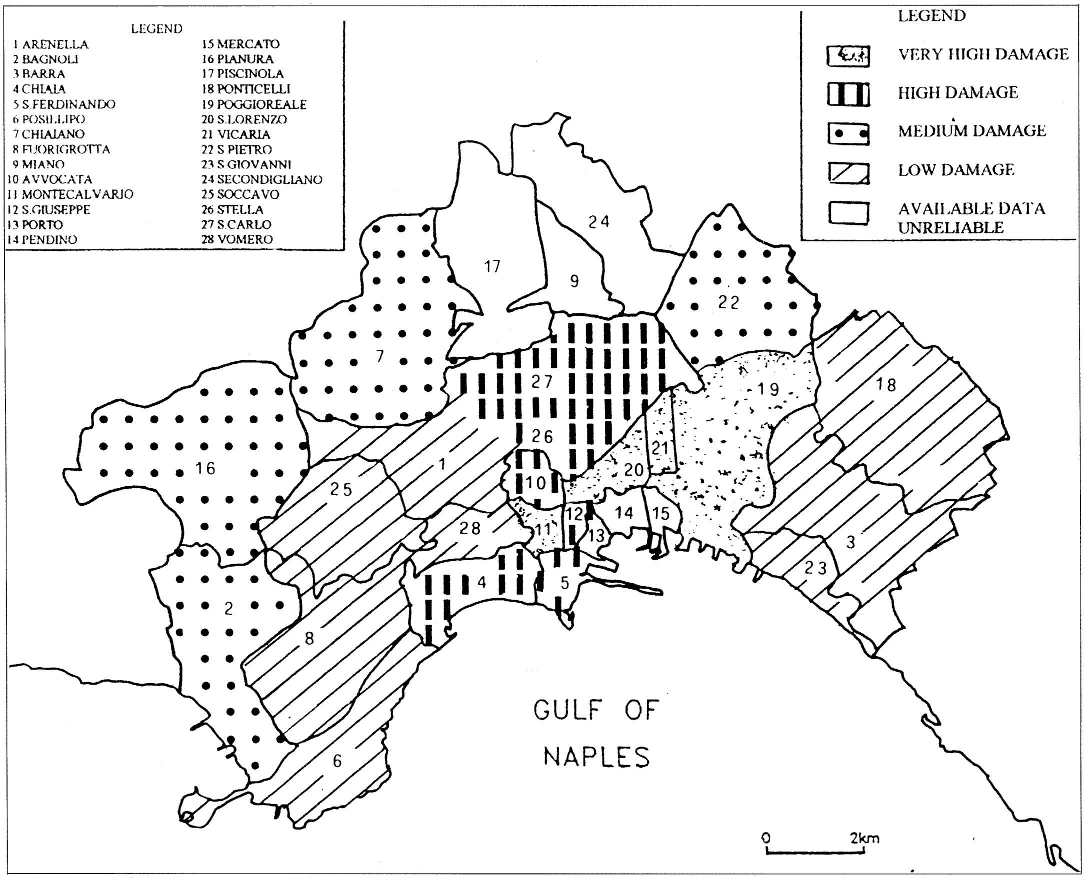


Fig. 1. Map showing the distribution of damage in Naples due to the 1980, Irpinia earthquake (modified from Esposito *et al.*, 1992).

Naples, lower peak ground accelerations might be expected on rock sites in the town. In addition, even if the epicentral distance is about 90 km, and therefore an increase in the peak ground acceleration with distance cannot be excluded (*e.g.* Suhadolc and Chiaruttini, 1985; Fäh *et al.*, 1993b), this increment should not exceed 30-40% of the maximum recorded at Torre del Greco. Hence, if for the historical buildings, the damage is easily explained by their degraded conditions, for the most damaged buildings in the eastern district, which are tall and made of reinforced concrete, it is necessary to consider the combined effects of the incident wavefield, the local soil conditions and the properties of the buildings.

The analysis of the strongest historical earthquakes, X and XI degrees on the Mercalli Cancani Sieberg (MCS) scale in the epicentral area, indicates that the maximum intensity observed in Naples is about VIII on the MCS scale for the most disastrous seismic event which occurred in Italian territory in December 1456. Intensity VII on the MCS scale was felt in Naples for the 1688, 1694 and 1805 historical earthquakes, as well as for the 1980 earthquake (Esposito *et al.*, 1992). The distribution of the damage caused by the historical earthquakes is obviously concentrated in the historical centre, but in 1805, the buildings present in the eastern part of Naples were completely destroyed.

Historical and archaeological data can be merged with geological information if synthetic isoseismals are computed considering the complete wavefield radiated from a point-source (Suhadolc *et al.*, 1988). This method, successfully applied to the modelling of the observed isoseismals of instrumentally recorded earthquakes (*e.g.* see Panza *et al.*, 1988; Panza, 1991), can easily be extended to historical earthquakes to infer their source mechanism (Panza *et al.*, 1991). For instance, it has been noted that, even if the observed isoseismals of the 1962 and the 1980 Irpinia earthquakes are differently elongated, the first being elongated perpendicularly to the axis of the Apennines and the second along the axis of the mountain chain, the source mechanism can be the same when the focal depths of the two events are assumed to be different. In accordance with the results of Panza *et al.* (1991), the focal depth of the 1962 event is greater than 12 km, *i.e.* the seismic source is close to the bottom of the thick, superficial sedimentary low velocity layers, while the focal depth of the 1980 earthquake is around 6 km. As a matter of fact, this is the method to assign a completely realistic seismogram to historical earthquakes, and hence to evaluate hazard in more rigorous terms.

The 1980 earthquake is the first strong event that occurred in the Southern Apennines, recorded by many instruments at different epicentral distances and in a wide range of frequencies. Several seismological studies considered the source geometry, the rupturing process, and the site effects (for a recent complete compilation of these studies see «Annali di Geofisica», 1993). The source process is complex, consisting of a main rupture episode (0 s subevent) followed by two smaller ones at about 18 s and 40 s from the origin time of the main episode. A general agreement exists about the geometry of the main rupture consisting of a fault dipping 60° toward NE and having a strike of about 315°. From levelling data (Pingue *et al.*, 1993), a fault dipping 20° toward NE is consistent with the second subevent (18 s), and another almost parallel to the main fault, but antithetic, dipping SW, is consistent with the third subevent (40 s). The largest moment release took place at a depth not exceeding 10 km, underneath the eastern flank of the Mt. Marzano ridge, near to the town of Laviano. This instrumental depth determination agrees quite well with the macroseismic depth estimate made by Panza *et al.* (1991).

The aim of this paper was (1) to perform the numerical modelling of the propagation of the wavefield, generated by the main rupture event of the 1980 earthquake, up to a profile trending N86°W, and located in a test area in the eastern district of Naples, and (2) to make an accurate and realistic evaluation of the seismic ground motion, taking into account the significant lateral variations which are present in the subsoil of this urban area.

For the computation of the local seismic response, we used (1) the standard one-dimensional method (computer program Shake), developed by Schnabel *et al.* (1972), that uses vertically incident *SH*-waves in a structure composed of plane parallel layers, here indicated as method 1, and (2) the hybrid method developed by Fäh (1992) and Fäh *et al.* (1993a,b), that accounts for the source and the propagation path, including anelasticity and local soil effects, here indicated as method 2. The results obtained with the two methods were compared in order to evaluate the possibilities of the commonly used 1-D computational techniques for reliable microzonation.

2. Numerical modelling of seismic ground motion for 2-D structures

Many computational techniques exist to estimate the ground motion at a site. The standard one-dimensional methods like Shake estimate the amplification of *SH* waves, vertically propagating through plane parallel layers of unconsolidated soils overlying the bedrock. Such techniques are very fast, but, are uncertain for structures which are characterized by strong lateral heterogeneities or sloping layers.

In these cases, at least two-dimensional techniques may be necessary for a useful and realistic estimate of the ground motion.

The numerical hybrid approach recently proposed by Fäh (1992) and Fäh *et al.* (1993a,b) can account for the source and the propagation effects, including anelasticity and local soil effects. The propagation of the waves from the source up to the complex two-dimensional structure is computed with the mode summation technique (Panza, 1985; Florsch *et al.*, 1991), and in the complex, laterally heterogeneous structure it is computed with the finite difference method. This hybrid approach combines the advantages of both mode summation and finite difference technique. With the mode summation method it is possible to simulate a realistic rupture process on the extended fault, as a sum of point sources, properly distributed in space and time. The path from the source up to the region containing the 2-D heterogeneities is represented by a 1-D layered anelastic structure. The resulting wavefield is then used to define the boundary conditions to be applied to the 2-D anelastic region where the finite difference technique is used. The hybrid approach has been developed for both *SH*- and *P-SV*-waves (Fäh, 1992; Fäh *et al.*, 1993a,b). Here only *SH*-waves are considered since the program Shake handles only this kind of waves.

3. Geological setting of the studied area

Naples is located on volcaniclastic soils and rocks (various types of tuffs) erupted by the Campi Flegrei volcanoes (fig. 2). The original material that forms the tuffs and the volcanic soils is in general the same, with the volcaniclastic rocks being the result of the hardening of the volcaniclastic soils by post depositional hydrothermal alteration. The tuff formation is either outcropping or is located some tens of metres below the ground surface. Its thickness ranges from twenty metres in the eastern district to two hundred metres under the Posillipo hill.

The volcaniclastic soils derive from different types of explosive volcanic activity. When the magma was richer in gas, the products were magma fragments. As a consequence of a sudden cooling, the magma was solidified in a glassy state and with a spongy structure. These products are the pumiceous lapilli that have a coarse grain size. When the magma was poorer in gas, or the cooling rate was slower, scoriaceous lapilli were erupted, having a crystalline centre and a glassy outer part. Lava fragments were often thrown out and lithic lapilli were formed. Generally these three different types of volcanic activity occurred simultaneously, but with varying intensity. Therefore the different volcanic products were generally present in a variable composition, and led to the formation of four different volcaniclastic soils: pozzolana, pumice, lapillus and scoria. The pozzolana is the most widespread soil in the Campi Flegrei and surrounding areas and is mainly formed by ash with a minor percentage of pumiceous lapilli. Pumiceous lapilli prevail in the pumices, as do lithic lapilli in the lapilli and scoriaceous in the scoriae. The lapilli are mostly present along the coast of the gulf of Naples. The pozzolana has often undergone weathering and rill-wash processes, and has been carried away, far from the original deposition site. Depending upon the intensity of such a process, the grain size becomes finer with respect to that remaining in the original condition.

Croce and Pellegrino (1967) distinguished six homogeneous geotechnical zones in Naples (fig. 2), characterized by a tuff formation deepening or disappearing towards NE and SW. The pozzolana is almost everywhere, but soil covering can include sands along the coast (zone 5), and alternations of volcanic soils, alluvial soils and organic materials (zones 3, 6).

The test area, chosen to estimate the seismic ground response, is a flat area in the eastern district of Naples (zone 6), delimited to the South by the gulf of Naples, to the East by the flanks of Vesuvius and to the North by the hills of Capodimonte and Capodichino. The water table is at a depth of a few meters. Several laboratory and field measurements have been conducted on pyroclastic materials of the Campi Flegrei (Guadagno *et al.*, 1992), and in particu-

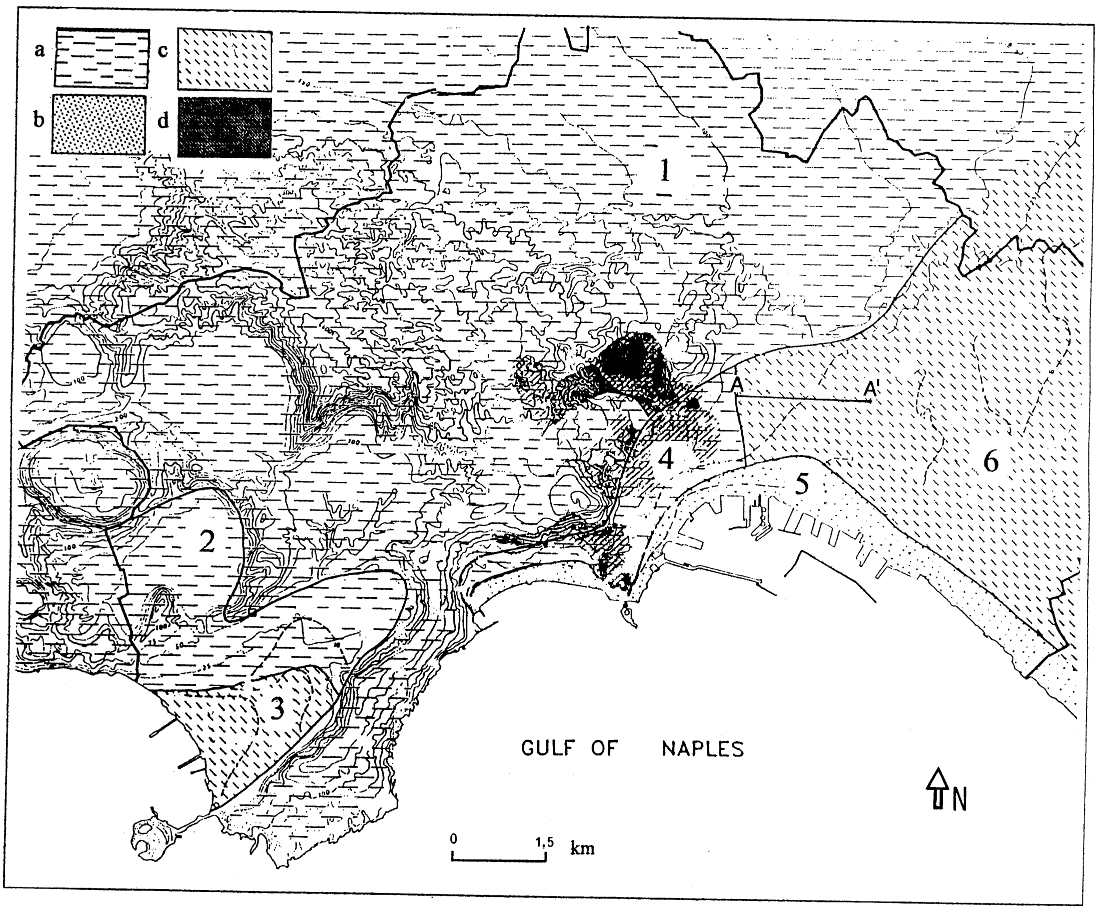


Fig. 2. Geotechnical map of Naples (modified from Croce and Pellegrino, 1967). Legend: 1) Pozzolana; 2) sea-shore sand; 3) alternations of volcanic soils, alluvial soils and organic materials; 4) cavities.

lar in our test area (Vinale, 1988), to define the geometry of the subsoil structures, and the physical (density, porosity, grain size, water content, etc.) and dynamic (*S*-wave velocities and damping ratios) properties of the materials.

The reconstruction of the main geological pattern is shown along a N86°W profile (fig. 3). The subsoil is mainly formed by man-made ground, alluvial soils (ashes, stratified sands, peat), loose and slightly cemented pozzolanas, yellow tuff and marine sands. The eastern area of Naples was a marsh, supplied by the Sebeto river and small streams, recently drained both for urban development and for the reduction of water supply. Water channels were later filled with a variety of materials: bricks and waste materials. The alluvial cover is formed by volcanic soils, moved away by streams and redeposited with different texture.

4. Seismic response

The causative fault of the 1980 earthquake is located about 90 km from the cross-section,

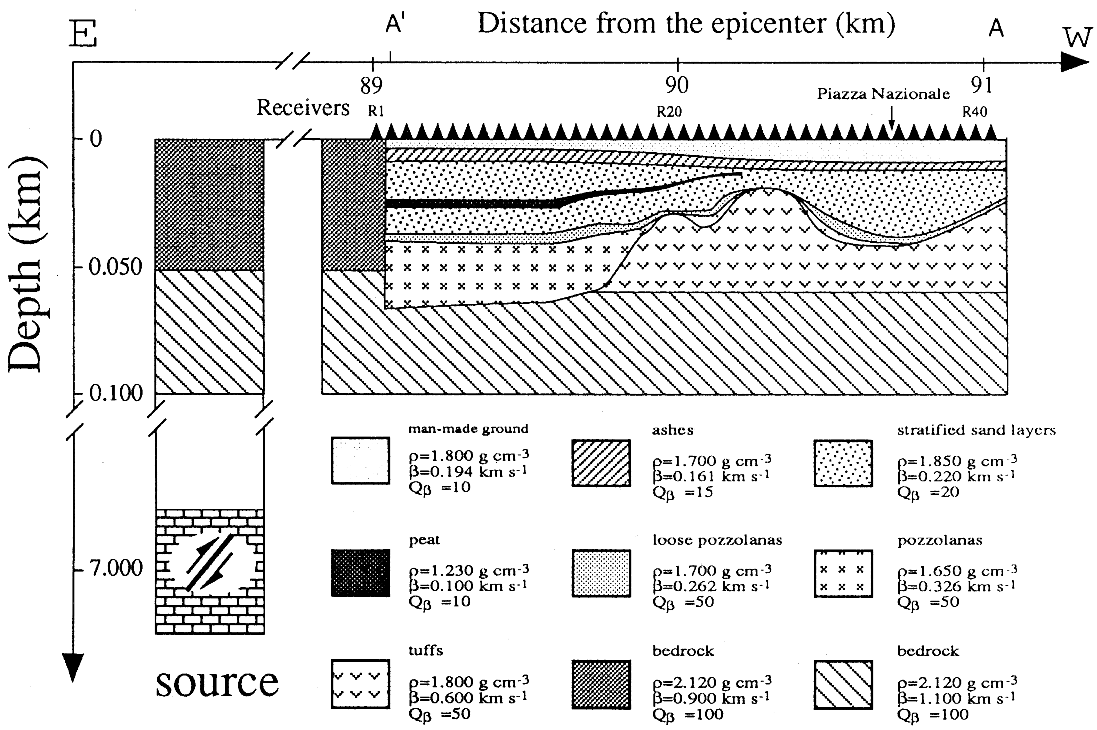


Fig. 3. Geological cross-section along the profile AA′ shown in fig. 2.

that we have taken as representative for the eastern part of Naples (fig. 3). The choice of the mechanism of the seismic source was made according to the mechanism of the main shock (0 s subevent) of the 1980 Irpinia earthquake: dip 65°, rake 270°, strike 315° and depth 7.0 km. The angle between the strike of the fault and the epicenter-cross section line is 36°.

The source is located in the laterally homogeneous part, and the propagation of the waves from the source up to the 2-D anelastic structure (fig. 3) was computed with the mode summation technique for the layered one-dimensional anelastic model representative of the path to the town of Naples (Vaccari *et al.*, 1990). Acceleration time series for *SH*-waves (fig. 4) were computed at an array of receivers over several different cross-sections: (1) the one-dimensional reference anelastic model for the bedrock, which represents the structural model for the region between the source position and Naples (table I), (2) the anelastic two-dimensional model with the peat layer, and (3) the same two-dimensional model without the peat layer. All scaling values were related to a source seismic moment of 10^{-7} Nm, and all signals normalized to the same value. The time scale is shifted by 22 s with respect to the origin time, and the distance between two receivers is 100 m.

The presence of unconsolidated sediments increased the signal's amplitudes and duration, which is more pronounced for the model without the peat layer. For the model with the peat layer, between receivers 1 and 15, the maximum amplitudes are similar to the maximum amplitudes observed for the one-dimensional bedrock model. This can be explained by the backscattering of wave energy at such a layer. These effects could be different if the peat layer is not laterally homogeneous, and the discussion of the effects of such fine details will be the subject of a future investigation.

The amplification and attenuation effects as a function of frequency can be identified through the analysis of the spectral ratios, that is the Fourier spectrum of the signals computed at the receivers in the 2-D structural model, normalized to the Fourier spectrum of the signals computed for the 1-D reference model (table I).

The maximum response spectrum of a simple oscillator is commonly used to quantify the ground motion for engineering purposes. We consider the spectral amplification for zero damping, which is defined as the response spectrum at a receiver in the 2-D structural model normalized to the response spectrum computed for the reference 1-D model. The spectral ratios and the spectral amplifications are computed in correspondence of the position of 5 receivers, representative of different stratigraphies in the 2-D section. Looking at the spectral ratios at the chosen receivers R7, R17, R23, R26, R33, the wide variability of ground motion is quite evident within a few hundred meters (fig. 5). The dominant peak moves from frequencies lower than 1 Hz (receiver R7), to

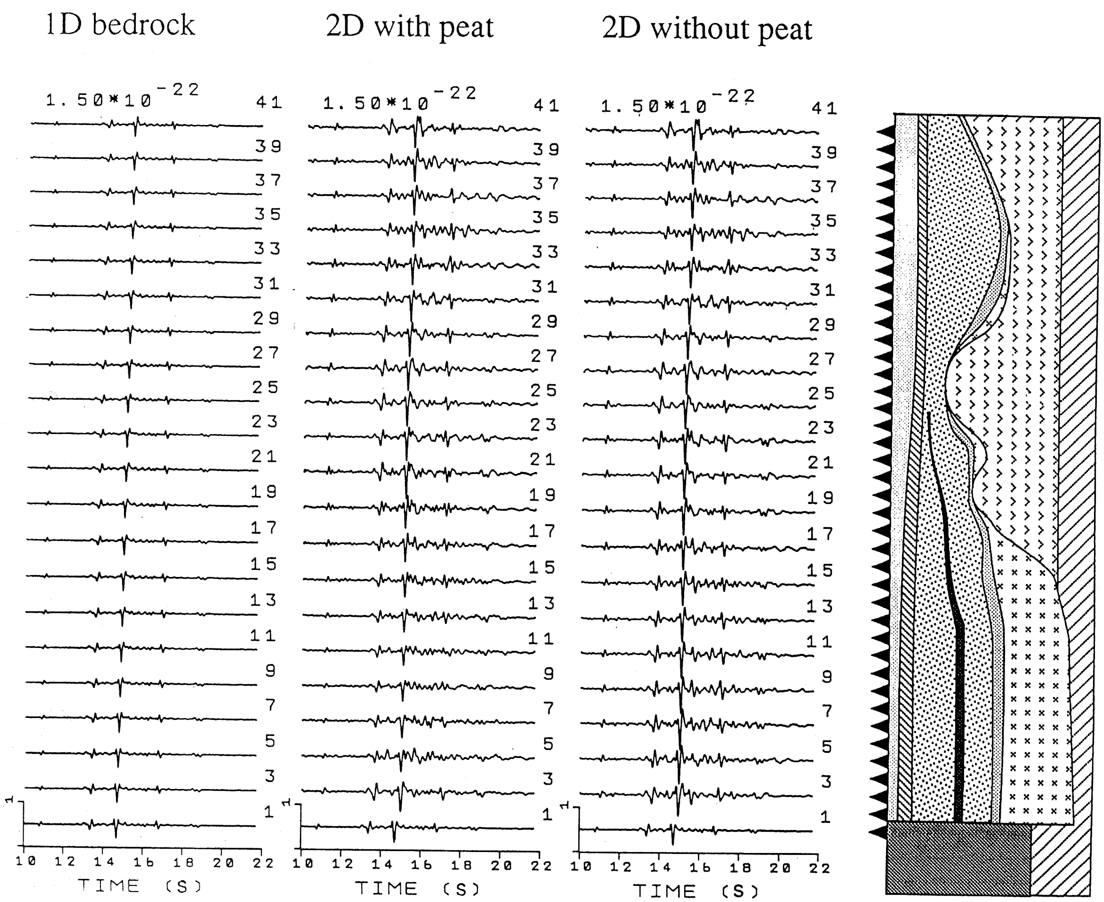


Fig. 4. Acceleration time series for *SH*-waves computed over the reference model (1D bedrock), the 2-D structural model with the peat layer, and the 2-D structural model without the peat layer.

Table I. The 1-D model representative of the path from the source of Irpinia earthquake to the city of Naples (from Vaccari *et al.*, 1990).

Thickness (km)	Density (g/cm^3)	*P*-wave velocity (km/s)	*P*-wave attenuation	*S*-wave velocity (km/s)	*S*-wave attenuation
.50000E–01	.21200E+01	.15500E+01	.64516E–02	.90000E+00	.27778E–01
.20000E+00	.21200E+01	.19000E+01	.52632E–02	.11000E+01	.22727E–01
.25000E+00	.21400E+01	.22500E+01	.29630E–02	.13000E+01	.12821E–01
.25000E+00	.21600E+01	.26000E+01	.25641E–02	.15000E+01	.11111E–01
.25000E+00	.21800E+01	.27000E+01	.74074E–03	.17000E+01	.29412E–02
.25000E+00	.22000E+01	.28000E+01	.71429E–03	.17500E+01	.28571E–02
.25000E+00	.22200E+01	.29000E+01	.68966E–03	.18000E+01	.27778E–02
.25000E+00	.22400E+01	.30000E+01	.66667E–03	.18500E+01	.27027E–02
.25000E+00	.22600E+01	.31000E+01	.64516E–03	.19000E+01	.26316E–02
.25000E+00	.22800E+01	.32000E+01	.62500E–03	.19500E+01	.25641E–02
.25000E+00	.23000E+01	.33000E+01	.60606E–03	.20000E+01	.25000E–02
.25000E+00	.23200E+01	.34000E+01	.58824E–03	.20500E+01	.24390E–02
.25000E+00	.23400E+01	.35000E+01	.57143E–03	.21000E+01	.23810E–02
.25000E+00	.23600E+01	.36000E+01	.55556E–03	.21500E+01	.23256E–02
.25000E+00	.23800E+01	.37000E+01	.54054E–03	.22000E+01	.22727E–02
.25000E+00	.24000E+01	.38000E+01	.52632E–03	.22500E+01	.22222E–02
.25000E+00	.24200E+01	.39000E+01	.51282E–03	.23000E+01	.21739E–02
.25000E+00	.24400E+01	.40000E+01	.50000E–03	.23500E+01	.21277E–02
.25000E+00	.24600E+01	.41000E+01	.48780E–03	.24000E+01	.20833E–02
.25000E+00	.24800E+01	.42000E+01	.47619E–03	.24500E+01	.20408E–02
.25000E+00	.25000E+01	.43000E+01	.46512E–03	.25000E+01	.20000E–02
.25000E+00	.25200E+01	.44000E+01	.45455E–03	.25500E+01	.19608E–02
.25000E+00	.25400E+01	.45000E+01	.44444E–03	.26000E+01	.19231E–02
.25000E+00	.25600E+01	.46000E+01	.43478E–03	.26500E+01	.18868E–02
.25000E+00	.25800E+01	.47000E+01	.42553E–03	.27000E+01	.18519E–02
.25800E+00	.26000E+01	.48000E+01	.41667E–03	.27500E+01	.18182E–02
.25000E+00	.26200E+01	.49000E+01	.40816E–03	.28000E+01	.17857E–02
.25000E+00	.26400E+01	.50000E+01	.40000E–03	.28500E+01	.17544E–02
.25000E+00	.26600E+01	.51000E+01	.39216E–03	.29000E+01	.17241E–02

frequencies slightly higher than 1 Hz (receivers R17 and R33), and to frequencies around 2 Hz (receivers R23 and R26). The maximum amplification factor of the ground motion is in general around five, and this value is exceeded only at receiver R17. A secondary significant peak is present at higher frequencies, between 2 Hz and 3 Hz at receiver R7, between 3 Hz and 4 Hz at receivers R26 and R33, and around 5 Hz for receiver R17. The damping effect of the peat layer is clearly shown by the comparison of the spectral ratios computed at the same

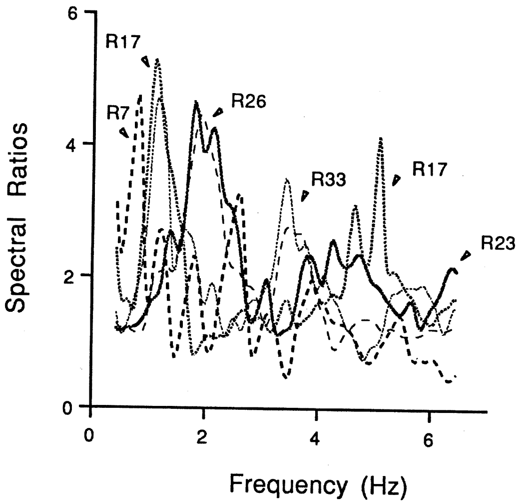


Fig. 5. Spectral ratios computed with the hybrid method at sites R7, R17, R23, R26, R33.

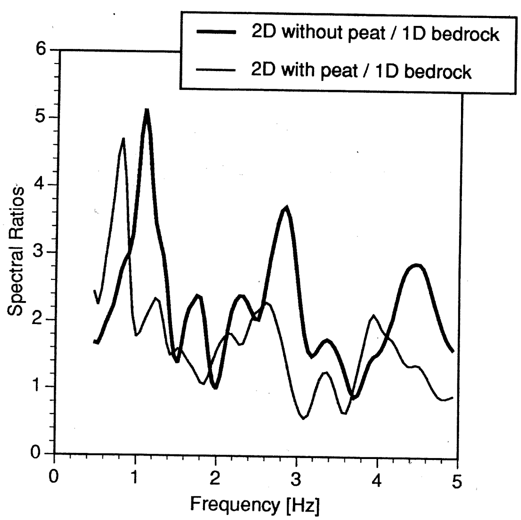


Fig. 6. Example of the effect due to the presence of the peat layer at site R9.

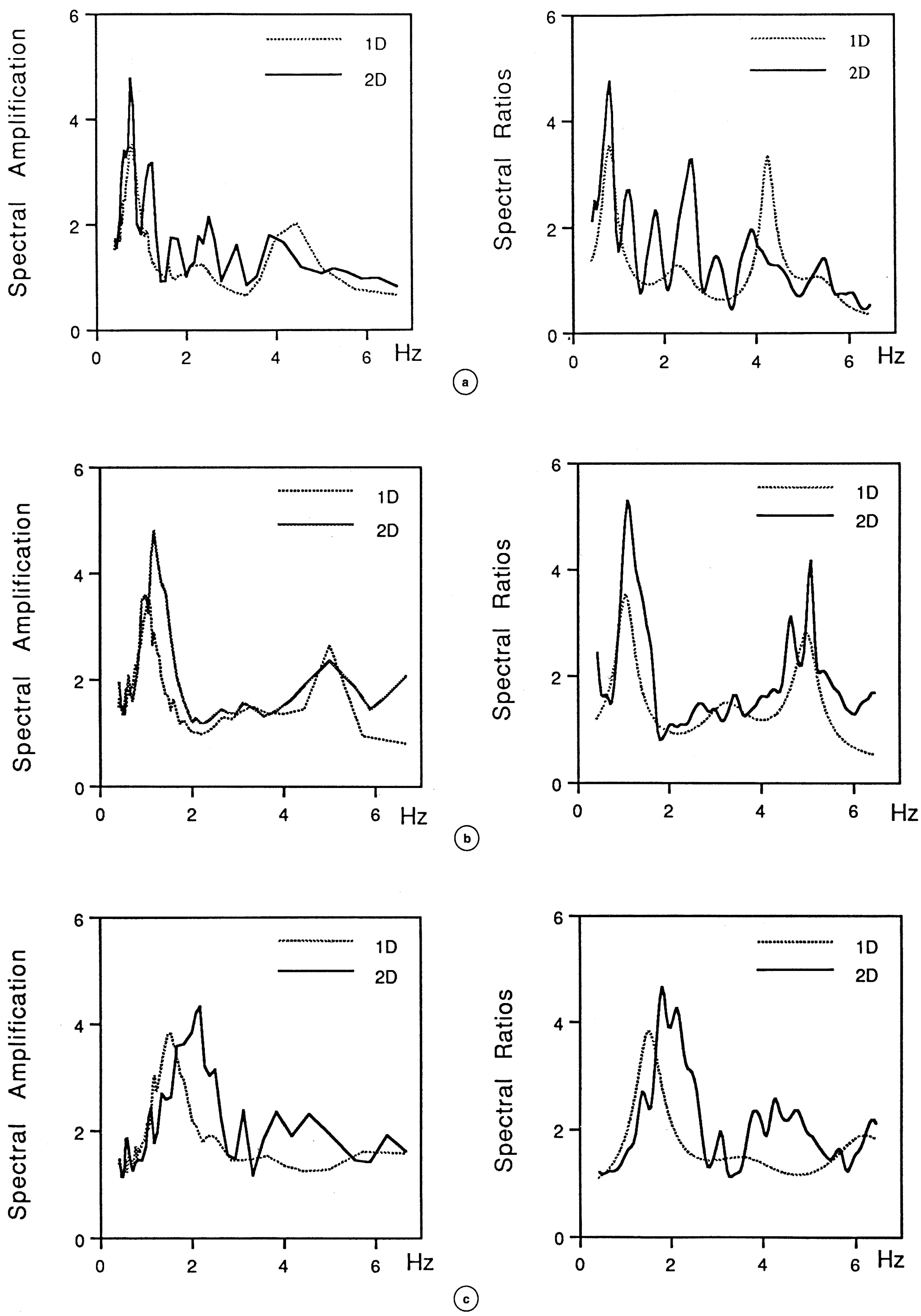
receiver R9 when the peat layer is removed (fig. 6). The maximum peak increases in amplitude and is shifted towards higher frequencies, when the peat layer is removed. The peat layer, even though with a thickness of only 3 m, significantly reduces the amplification effects induced by the unconsolidated sediments.

The discrepancies between the amplifications computed with method 1 and method 2 are illustrated in fig. 7a-e. At receiver R7, the dominant peak is estimated at the same frequency by both methods, but the amplitude obtained with method 1 is 30% smaller than that obtained with method 2. Moreover, other peaks, at frequencies which are very important for engineering purposes, and clearly visible in the results obtained with the hybrid method, are absent in the modelling made with method 1. The spectral ratios and the spectral amplifications for zero damping, obtained with method 1 and method 2, have similar peaks at receiver R17, but the amplification computed with the 1-D method is underestimated with respect to that determined with the 2-D method. At receiver R23 a frequency shift of the main peak is observed. The picture changes for receivers R26 and R33, as the spectral amplifications computed with method 1 overestimate those obtained with method 2, even if they have a similar shape.

5. Discussion

The main effort that is necessary to mitigate the seismic hazard is the definition of a correct seismic response, both in terms of peak ground acceleration and spectral amplifications. It is well known that these factors depend upon the mechanical characteristics of the local soil conditions, and the characteristics of the expected earthquake, like focal mechanism, hypocentral depth, epicentral distance, and magnitude or scalar seismic moment. The formulation of good building codes for engineers, should rely on the information which is supplied by many different disciplines, such as seismology, history, archeology, geology and geophysics. If properly used, synthetic seismograms may represent a fundamental tool to take into consideration most of this information simultaneously, with the important practical result of effectively reducing seismic vulnerability.

Naples represents a typical example of a non-seismogenic area, but close enough to


Spectral Amplification
Spectral Ratios
1D
2D
Hz
0
2
4
6
a
b
c

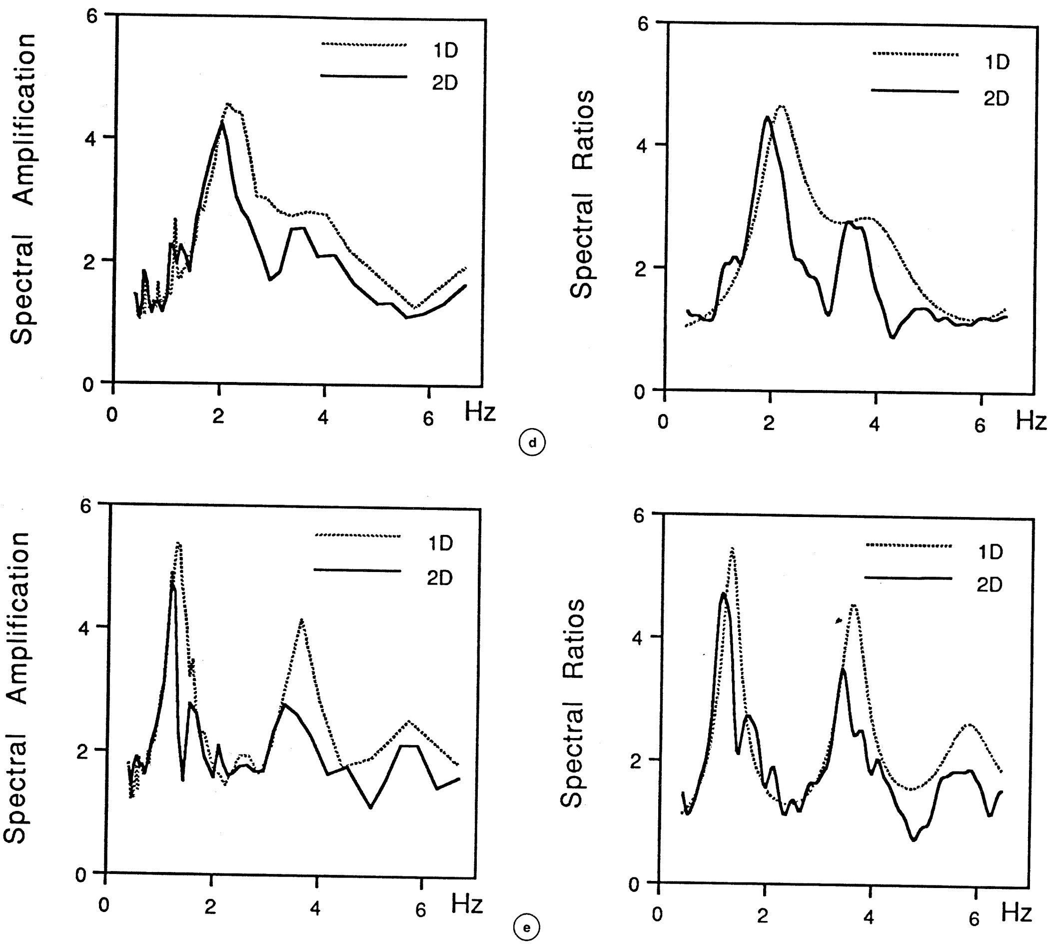


Fig. 7a-e. Spectral amplification for zero damping and spectral ratios computed with method 1 and method 2 at site R7 (a), at site R17 (b), at site R23 (c), at site R26 (d), at site R33 (e) (see fig. 3 for location). As in figs. 5 and 6, spectral ratios are smoothed; this is not the case for spectral amplifications, therefore spectral amplifications represent a quite reliable parameter, much more stable than spectral ratios.

seismogenic areas to suffer serious damage both because of the degraded conditions of the historical built-up environment and because severe local site amplification occurs. On the other hand, the high density of population and the kind of built-up environment to be protected increase the vulnerability of some areas of Naples, and consequently the seismic risk. Vulnerability may be reduced through the retrofitting of ancient buildings and monuments and through the design of reinforced concrete structures able to resist seismic shaking. Serious regulations are required since monuments must not be damaged by random injections of concrete. Sound anti-seismic criteria can be reliably based only on the knowledge of site seismic response, both in terms of peak ground acceleration and frequency content.

Ground motion modelling made with complete *SH*-wave seismograms shows that the superficial soil deposits composed of pyroclastic and alluvial materials, with lateral discontinuities, are responsible for an increase in amplitude and duration of the signal relative to the bedrock. Such an effect is reduced when a thin, laterally heterogeneous peat layer is present. Peak ground accelerations on rock sites and on surficial soil deposits with peat are similar, and they are about half of those observed on soil deposits without peat. Relevant differences are observed in the time series computed along the 2-D structure and they are even more clear when the seismic ground motion is considered in the frequency domain (fig. 5). It is evident that the unconsolidated sediments amplify particular frequencies contained in the seismogram computed for the 1-D reference model. Hence the built-up environment along the profile has to resist shear stresses up to five times larger than that on the rock site.

6. Conclusions

As a first step for the mitigation of seismic risk, the seismic ground motion of a flat test area in the eastern sector of Naples was modeled along a profile trending N86°W, considering as source the main shock of the 1980 Irpinia earthquake. Discrepancies are found between the amplifications computed with the 1-D standard method (method 1) and the more realistic 2-D hybrid method (method 2). These differences cannot be ignored when formulating building codes and retrofitting the old built-up environment. In the presence of a peat layer, for the dominant peak, the amplifications computed with method 1 are smaller than the ones computed with the more realistic method 2, while for the second significant peak random mismatches are observed. This is a clear evidence of the danger intrinsic in the application of method 1 for vulnerability assessment, even in a flat area. When the peat layer is absent, a similarity exists in the shape of the spectral amplification functions computed with the two methods, but method 1 overestimates the effects with respect to the more realistic method 2. Thus the use of the guidelines based on method 1, may imply unnecessary, higher costs for the reduction of vulnerability.

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