State-of-the-art in seismic microzonation, advances in Italy from 1980 to the present

Livio Sirovich[1][*] and Andrea Del Grosso[2]
[1] *Osservatorio Geofisico Sperimentale, Trieste, Italia*
[2] *Istituto di Scienza delle Costruzioni, Università di Genova, Italia*

Abstract
Current research in Italy is mostly devoted to calculating the seismic response of small to medium areas by means of 2D models (in the case of relatively small sites) or of several 1D models, the results of which are then smoothed throughout the area (in the case of larger, but relatively simple, areas). The pseudo-spectral method is also applied to the response of valleys, ridges and subsurface morphology. Some very peculiar urban and geomorphological settings of towns in the hills were modeled too (slopes highly tunnelled by cellars or densely urbanized sites). Microtremors and coda waves were also investigated. The importance of uncertainties in the value of some geometrical/mechanical parameters of the models was treated by two groups of Italian researchers.

1. Introduction

The subject of site effects during ground motion has been discussed for a long time among seismologists, engineers and geologists. To date, strong evidence has been accumulated from both experimental observations and theoretical studies, pointing toward the importance that site effects may have on intensity, duration, frequency content of earthquakes, and consequently on damage distribution. Recent studies conducted on destructive earthquakes (*e.g.*, Gazetas *et al.*, 1990, Celebi *et al.*, 1989) have confirmed how the phenomenon can show significant complexity.

Basically, site effects can be associated to the following mechanisms:

– scattering of the waves produced by topographic features of the site and/or the underground morphology;
– filtering of the waves by surficial soil deposits, and sometimes their non-linear behaviour;
– development of localized instability phenomena (slides, liquefaction, etc.).

Until some years ago, it was thought that rocky sites were able to give amplification factors less than 2 for frequencies higher than 5 Hz in Fourier amplification spectra, whilst factors for soft sites and for frequencies below 5 Hz ranged up to 2 or 3. Now it has been recognized (*e.g.*, Aki, 1988) that amplification factors for velocities and displacements can reach the value of 10 and that the previous underestimation was due to a poor classification of soils.

Prediction of site effects is therefore one of the most important tasks in performing microzoning activities. State-of-the-art reports on such studies were produced by Sanchez-Sesma (1987) and Aki (1988) to which the reader is referred for detailed discussions. An updated report has been presented by Faccioli (1991).

Various methods (empirical, analytical as well as numerical) are available to treat the problem. These methods can be based upon mathematical models or statistical databases, and require different degrees of knowledge about source mechanisms, subsoil conditions or geomechanical properties of soils and rocks. Research progress during the last decade suggests the following brief observations:

– empirical methods based on simple soil classifications or «rule of thumb» derived from limited statistics may be in error of several units in estimating the amplification factors;

– although the shear wave velocity of surficial layers is recognized as one of the dominant parameters affecting local site response, and reliable models (SHAKE, LASS, CHARSOIL, etc.) to evaluate the 1D amplification are available, experimental evidence shows that 2D scattering effects may be even more important than the filtering effects of soil deposits;

– sophisticated analytical/numerical methods have been developed for the study of the 2D situations, which are able to reproduce the most relevant aspects of the seismic wave propagation problems with sufficient accuracy (discrete wavenumber, ray methods, finite elements, etc.);

– experimental/statistical methods (site response spectra, local earthquakes, coda waves, etc.) can also be used to estimate the amplification characteristics of the real sites.

More powerful computer techniques such as vectorization or parallelization may render present numerical tools suitable for even wider applications. However, most of the methods possess advantages and disadvantages rendering them of greater or lesser suitability under general conditions, and may require levels of investments and developement time scales incompatible with the objectives of risk reduction policies in small urban areas. In particular, the following characteristics make microzoning in Italy, and in the Mediterranean basin in general, very peculiar.

– The extension of urban areas is small compared to those of northern Europe or America. This means that the investigation and modelling of site effects usually involves areas from a few hundred meters to a few kilometers wide.

– Urban centers are characterized by a high to very high density of buildings. In addition, at least some of the centers are very old, and often consist of nested constructions and reconstruction. Consequently, detailed subsoil exploration can be very expensive and sometimes impractical.

– Microzoning is mostly needed as part of urban planning or replanning programs, owing to reconstruction, expansion of urban areas and seismic-risk reduction in existing nuclei.

– Seismicity, at least in Italy, is characterized by relatively frequent events of moderate to low intensity and relatively rare strong-motion events. On the other hand, Italian seismic history is very long and well documented, so that site effect studies based on historical seismic damage can be sometimes performed.

It is probably due to the above reasons that, apart from local response studies undertaken for the siting of nuclear power plants, and after a few investigations based on microtremors or on the Medvedev method, the first microzonations of significance (Marcellini, 1986) were conducted only after the Friuli earthquake of 1976 and related to Tarcento (Brambati *et al.*, 1980) and Ancona (Various Authors, 1981).

Since then, a great effort has been devoted by the Italian scientific community and by research bodies to deepening knowledge of site effects during Italian earthquakes, to producing or upgrading the tools available for microzoning studies, and to gaining more experience.

2. Current research in Italy

Current research in Italy is mostly devoted to calculating the seismic response of small-to-medium areas by means of 2D models (in the case of relatively small sites) or of several 1D models, the results of which are then smoothed throughout the area (in the case of larger, but relatively «simple», areas).

Faccioli and his co-workers (*e.g.*, Paolucci, 1989) apply the pseudo-spectral method to the response of semi-cilindrical and triangular valleys, to triangular ridges, and attempt an application to the clayey valley of Mexico City. Spectral and F.E.M. methods are presently being developed also at OGS for anisotropic media for various topography and subsurface structures (*e.g.*, Seriani and Manzella, 1989; Carcione, 1990; Seriani and Priolo, 1991, see fig. 1).

Programs FLUSH and QUAD-4 were applied to the hill in the city of Avellino by Corsanego *et al.* (1984c); see fig. 2.

An extensive application of 1D models was made by Vinale (1988) who calculated the response of 18 sites inside an area of about 1.5 km^2

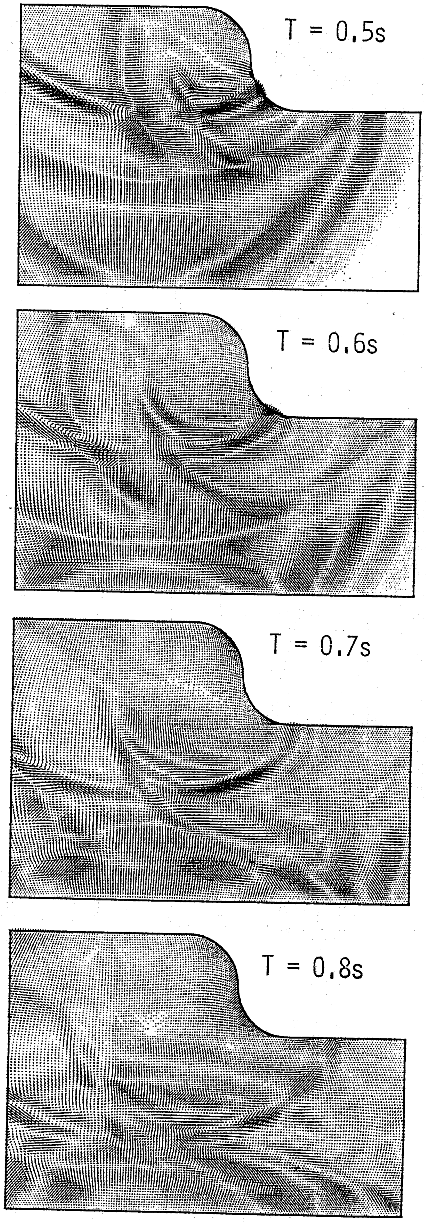

Fig. 1. A 2D F.E.M. experiment performed at O.G.S.. In this case the elastic wave propagation at various time steps is shown in a homogeneus medium with a smooth step on the free surface. The source is a point pressure impulse in the interior. Absorbing boundary conditions were applied on both lateral sides; a rigid bounday condition was defined at the bottom (from Seriani and Priolo, 1991).

by means of the SHAKE program. Vinale does not trust «simple» correlations between seismic response and basic geotechnical features; he quotes as evidence that the strict application (using the impedance of the first 10 meters of sediment) of the Medvedev method fails in estimating the seismic response, which appears to be controlled mostly by the entire thickness of the overburden (see fig. 3). Crespellani (1988), Crespellani *et al.* (1989), Vannucchi (Editor, 1989), Brignoli *et al.* (1991) examined a rather homogeneous area of 2.6 km^2 near Florence, with 60 m of fine cohesive deposits over 240 m of overconsolidated sediments; only one 1D model (SHAKE) was necessary to simulate the response of this uniform area. Renner *et al.* (1988), Siro and Priolo (1989, 1990), developed a revised version of the program CHARSOIL (Priolo and Siro, 1989; see fig. 4) to model the 1D seismic response of a certain number of soil columns inside two heterogeneous areas 0.6 km^2 (14 models) and 0.4 km^2 (5 models) wide, respectively. In both cases, the extreme complexity of the local geology (also partly shadowed by two hamlets) did not allow the production of a microzonation map. Siro and Priolo (1990) give a nomogram (see fig. 5), obtained by modelling, to estimate roughly the seismic response of the different local environments in one hamlet, once the underground stratigraphy is known.

The very peculiar urban and geomorphological setting of the towns in the Alpine and Apenninic Chains stretched the abilities of some researchers modeling the response of hills highly tunelled by cellars (Corsanego *et al.*, 1984c; see fig. 6) and of densely urbanized sites (Corsanego *et al.*, 1984c; see fig. 7).

The so-called coda waves method was applied also in Italy by Del Pezzo and Martini (1989); this method can furnish promising results where data on minor seismic activity are available, but perhaps in this case it was (unavoidably) applied to a non-ideal case.

Also the problem of using microtremors has recently been tackled with up-to-date techniques by two groups of researchers. Hough *et al.* (1990) made simultaneous recordings in a site on alluvium and one on rock. Rovelli *et al.* (1989) found time-invariant spectra of microtremors in the ENEA-ENEL strong-motion station of S. Rocco-

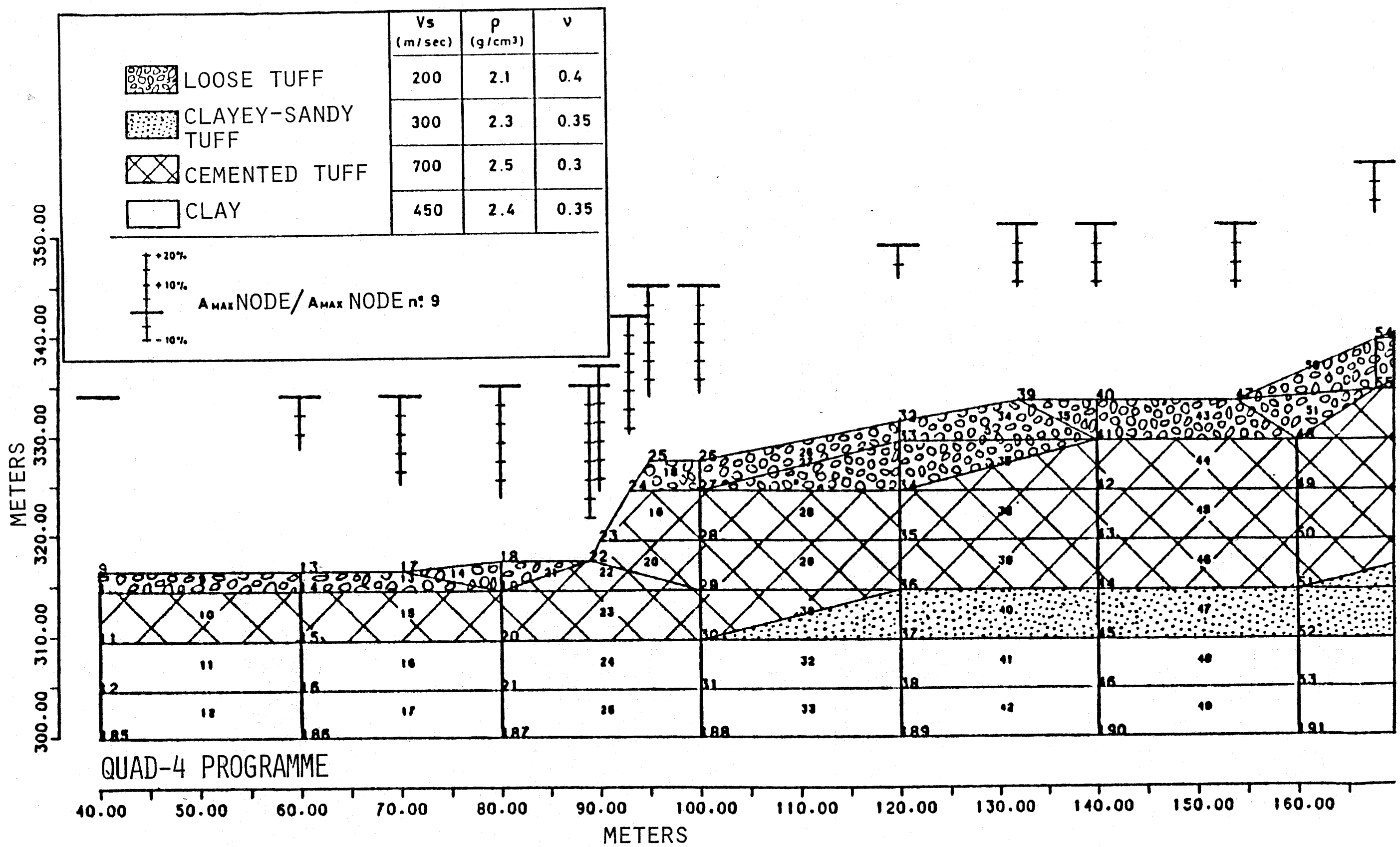

Fig. 2. 2D modelling of the seismic response of the Avellino hill by means of the QUAD-4 programme. The table shows the shear wave velocity, the unit weight and the Poisson's coefficient of the rocks. The bars indicate the relative amplification of all nodes on the surface of the hill with respect to the first node on the left (from Corsanego *et al.* 1984c. Redrawn; partim).

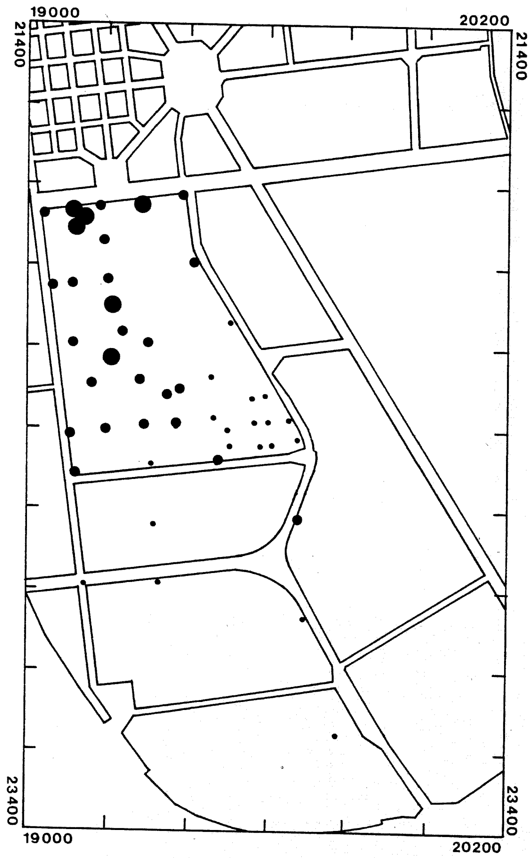

Fig. 3. Period of the first vibratory mode of the whole overburden. Small dots: over 0.89 s; medium dots: between 0.89 s and 0.50 s; big dots: under 0.50 s. In this particular case (owing to the frequency content of the assumed forcing seismic action), the maximum amplification factors were forecast in the area where the big dots (short periods) are more frequent. (Redrawn from Vinale, 1988.)

Cornino (see fig. 8). Siro (1986) found that the spectra varied strongly by time in a Po Valley site during the different seasons of the year (see fig. 9).

The importance of uncertainties in the values of some geometrical/mechanical parameters of the models was treated by Faccioli *et al.* (1989) who modelled, in 1D and 2D, the response of media with S_H propagation velocity given by the sum of a derministic trend and a stochastic fluctuation. Del Grosso *et al.* (1989) applied the response surface method (known from the statistics of experiments) to describe mathematically the behaviour of a series of models which are thought of as systems whose response cannot be given in closed form due to the uncertainty in some parameters. It is shown, for example, that on the surface of a homogeneous stratum ranging from 11 to 29 m in depth and from 100 to 400 m/s in V_S, the relative amplification can be higher than 7 (see fig. 10).

3. Concluding remarks

Even if quantitative evaluations (from experimental measurements or from modelling) are always preferable, there is often the need for less expensive tools, at least for a preliminary analysis. Aki (1988) quotes, for example, the interesting correlation between amplification and mean impedance of the overburden, or void ratio, and emphasizes the influence of the depth of the Holocene sediments on the amplification that was evidenced during the extensive studies for the microzoning of the Los Angeles area (Ziony, Editor, 1985). It is our opinion that in certain instances (flat morphology, depth of soft sediments of the same order as the incoming wavelength, as is sometimes the case in Italy), an evaluation of the mean «stiffness» of the surficial sediments (not necessarily within the first 10 m) and of the first vibratory mode of the entire overburden can help in giving a preliminary idea of the relative amplification factor in an area.

In this perspective, it is worth noting that, as regards Italian researchers, a tentative comparison between quantitative modelling and simplified procedures was made by Renner *et al.* (1988), while Carpaneto *et al.* (1984) suggested how to estimate the frequency of the principal mode of an anelastic stratum, Lojelo and Sanò (1985) did the same for an elastic case — assuming a continuous variation with depth in the elastic characteristics of the stratum — and Vinale and Simonelli (1983) assumed a particular distribution for V_S.

Studies on both quantitative and approximate models for local site response and on their use in microzoning activities are presently being done

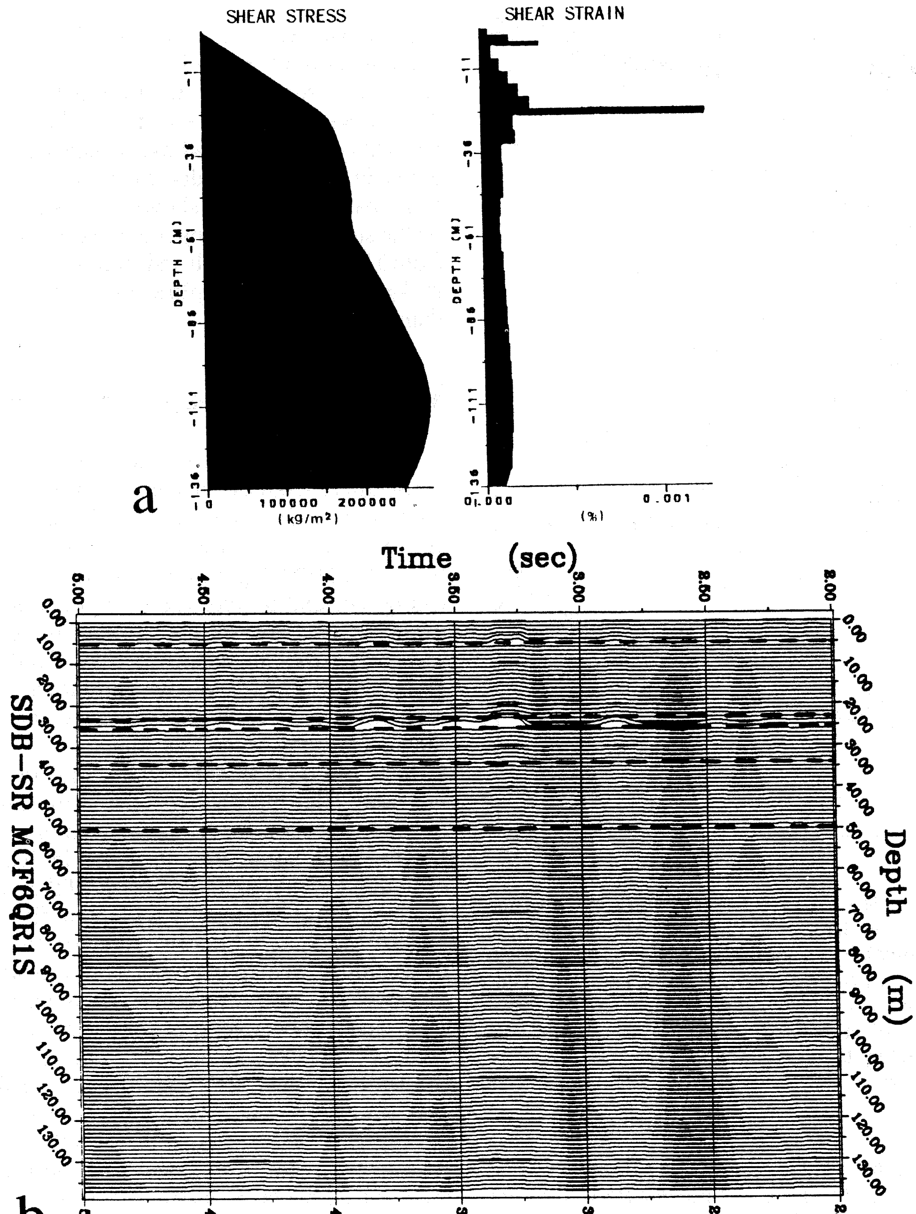

Fig. 4. a) Maximum shear stress and strain *versus* depth computed in the ENEA-ENEL Cornino site for the maximum shock recorded at S. Rocco in 1976. Non-linear Ramberg-Osgood model; CHARSOIL programme with elastic half-space boundary condition. b) Time-dependent shear strain at the Cornino site: time goes from right to left. Strain negative variable-area time-histories are shown. Dashed horizontal lines indicate the subdivision of the model. Maximum shear strain is encountered mainly inside the softest layer between –23 and –25.5m (from Priolò and Siro, 1989).

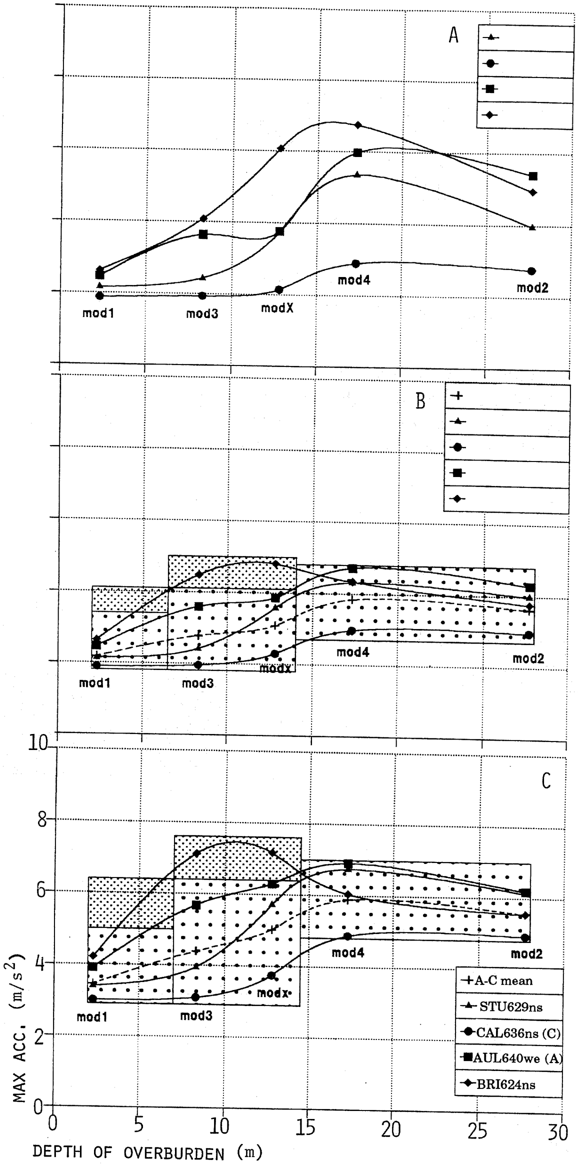

Fig. 5. a) Maximum calculated horizontal surface acceleration from five experimental models in the hamlet of S. Gregorio Magno (SA, Southern Italy) when excited with four scaled 1980 strong-motion accelerograms. The principal cause of the different responses of the models was found to be the depth of the overburden (usually overconsolidated clay and silt) lying on the bed-rock (limestone). The calculation was made using an updated version of CHARSOIL programme. Elastic response is shown in this figure. All forcing actions transmitted by the bed-rock were scaled to 0.93 m/s^2. b) As in fig. a), but with Ramberg-Osgood models. Note lower PGAs on the surface and shifting of the peak response towards thinner models especially when the high-frequency forcing accelerogram is used. The shadowed areas give a tentative nomogram to estimate roughly the peak response of sites ranging in depth from 2 to 28 m when low-to-medium frequency input motion, or high frequency (densely dotted areas), are adopted or expected. c) As in fig. a), but with the forcing actions scaled to 1.47 m/s^2 on the bed-rock). Note the more evident shift of the peak response towards the thin models (from Siro and Priolo, 1990).

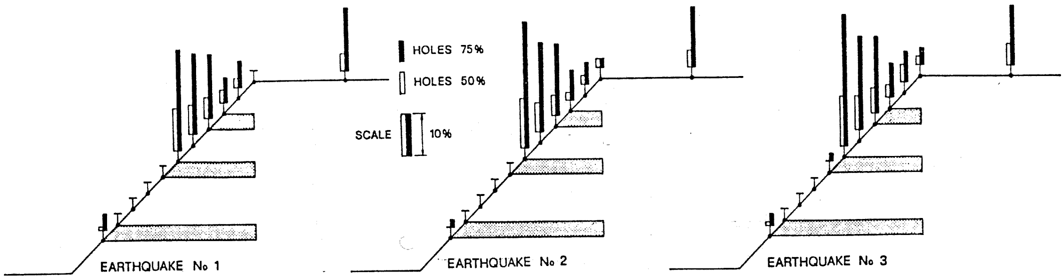

Fig. 6. The effect of the presence of deep cellars (holes) on the seismic response of a slope. Percentage histograms of peak response acceleration increase (from response spectra at 5 percent damping); two percentages of holes were considered, their presence being simulated by simply reducing the unit weight and the elastic moduli in the modelled volume of the cellars. Programme FLUSH was used (from Corsanego *et al.*, 1984a).

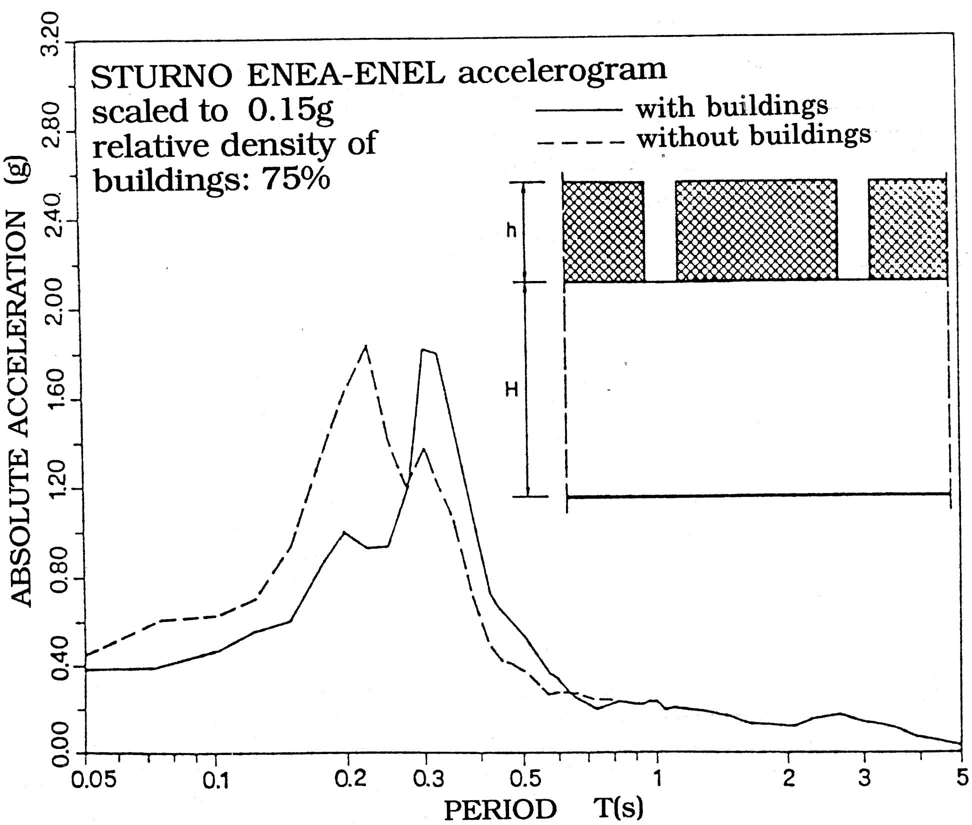

Fig. 7. The effect of the presence of a densely built town centre on the seismic response of the soil. The adopted model (section): soil supporting many buildings. Spectral response (absolute acceleration) of the model (with buildings) compared with that of the free surface (dashed-line, without buildings). Programme FLUSH was used (from Corsanego *et al.*, 1984b).

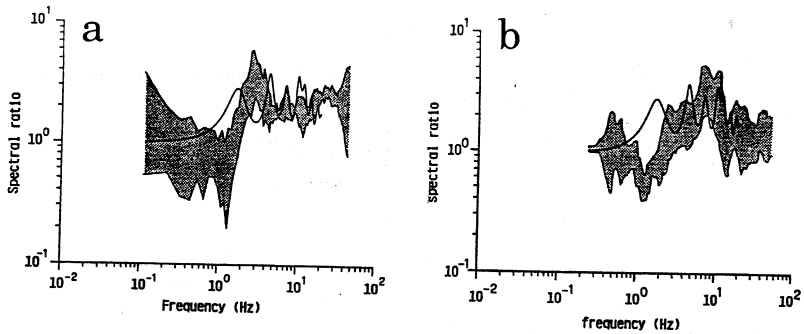

Fig. 8. Spectral ratios between the Cornino and S. Rocco ENEA-ENEL accelerometer stations computed on the horizontal components of the 1976 strong-motion records (a)), and microtremors (b)). The shadowed areas represent the intervals of 1 standard deviation around the mean value. The transfer function derived from 1D numerical modelling (solid line) was superimposed for the sake of comparison both in a) and b) (from Hough *et al.*, 1990). (Comment: there is a reasonable agreement between shadowed areas in a) and in b) only if a (3÷5) Hz shift is made in one of the two figures.)

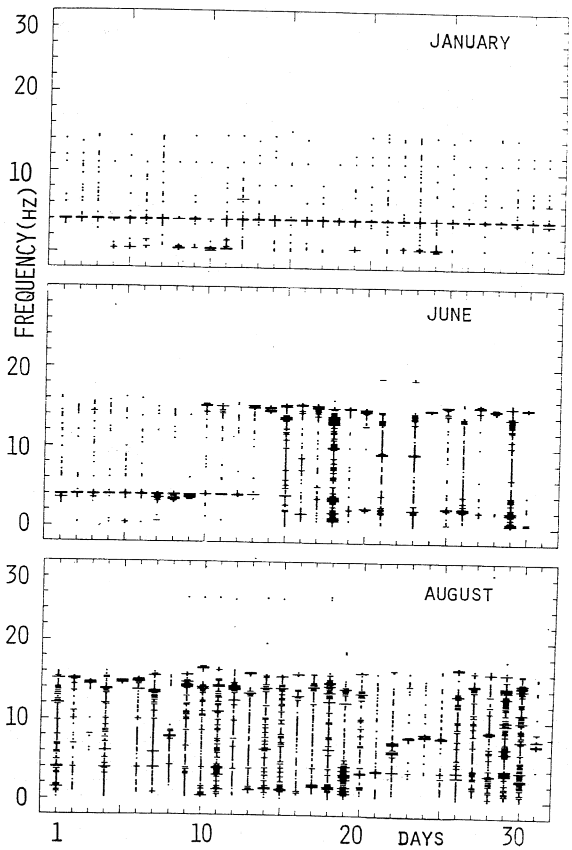

Fig. 9. Nightly microtremor spectra recorded in a 1000 m deep alluvium site in the Po Valley (first oscillatory mode of the various alluvial strata ranging from 0.1 to 0.7 Hz) in different seasons of the year. Observe how the spectra change in time and do not coincide with the quoted oscillatory mode for body waves (from Siro, 1986).

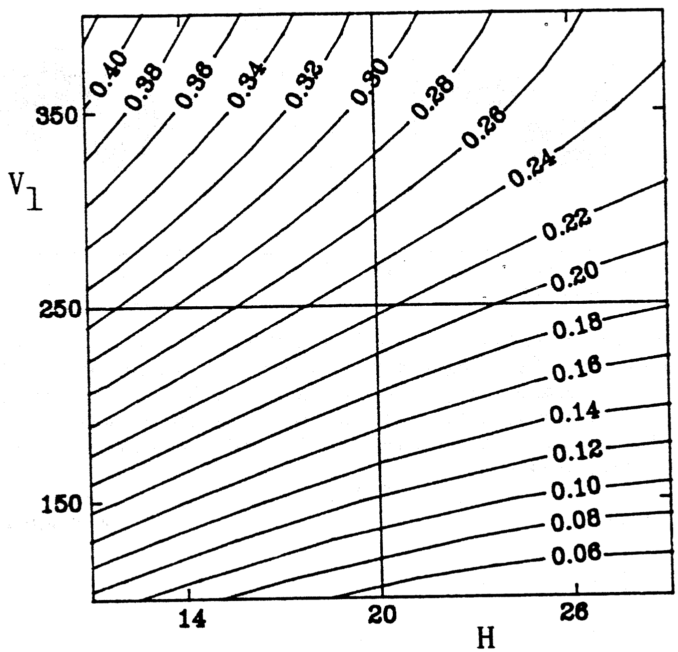

Fig. 10. Parametric analysis of the seismic response on the free-field of a 1D soil profile with an overburden of depth H (in between 10 and 30 m) upon bed-rock with V_S = 2000 m/s. V_l is velocity of shear waves inside the overburden. Values of maximum response (from 0.06 to 0.40) are in g; maximum acceleration on the bed-rock is 0.20 g (from Del Grosso *et al.*, 1989).

by several researchers from Universities, C.N.R., I.S.M.E.S. and O.G.S., under the coordination of the «Gruppo Nazionale per la Difesa dai Terremoti» (CNR).

(*) Previously: L. Siro. Recently, the author reassumed his original family-name that had been changed in 1928.

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