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***Advanced Criteria of Seismic Zoning
and Synthetic Seismograms***

presented by:

Giuliano F. PANZA

Università degli Studi di Trieste
Dipartimento di Scienze della Terra
Via Weiss 1
I-34127 Trieste
Italy

These are preliminary lecture notes, intended only for distribution to participants.

ADVANCED CRITERIA OF SEISMIC ZONING AND SYNTHETIC SEISMOGRAMS

G.F. Panza^(1,2) and F. Vaccari^(1,3)

⁽¹⁾University of Trieste, Trieste, Italy

⁽²⁾International Centre for Theoretical Physics, Trieste, Italy

⁽³⁾Gruppo Nazionale per la Difesa dei Terremoti, Rome, Italy

ABSTRACT

A brief revision of the traditional deterministic and probabilistic methods of first order seismic zonation, outlining their limits and possibilities, indicates that they can only lead to a kind of "post-event" zonation, which has a limited local validity. The strong influence of lateral heterogeneities and of source properties on the spatial distribution of Peak Ground Acceleration (PGA) and of the Total Energy of ground motion (W), indicates that the traditional methods require a deep revision.

The method we have developed and applied to a first-order seismic zoning of the whole Italian territory and to the microzoning of specific objects, being based on the computation of synthetic seismograms, makes it possible and necessary to take source and propagation effects into account, fully utilizing the large amount of geological and geotechnical data, already available. Even though it falls in the domain of deterministic approaches, the method is very suitable for inclusion in the definition of new integrated procedures which combine probabilistic and deterministic approaches and allow us to minimize the present drawbacks which characterise the two methods when they are considered separately. If the seismotectonic regime is well known, a very important practical aspect of our deterministic approach is the immediate capability to direct the rescue intervention of the Civil Defence where the greatest damage is expected, by drawing post-event synthetic isoseismals for the source regions. Detailed modelling of ground motion for realistic two-dimensional media is a low-cost but very powerful tool for the prevention aspects of Civil Defence since it allows the computation of realistic seismic input for important structures based on the definition of a wide set of possible scenarios, which can be immediately used in the design of new seismo-resistant constructions and in the reinforcement of existing structures.

1. INTRODUCTION

Seismic zoning is the division of a geographical region into smaller areas in each of which an equal relative severity of ground motion is expected. Its practical advantages as a technical step towards the mitigation of seismic hazard were first identified at the beginning of this century. Traditionally seismic zoning was one of the most important elements of post-earthquake surveying, proving essential for the choice of the urban and non-urban areas safest or best suited for the development of new settlements, and as a guide to reconstruction. More recently the guidelines of the International Decade for Natural Disaster Reduction (IDNDR), organised by the United Nations for the drawing up of pre-catastrophe plans of action, have led to the consolidation of the idea that zoning can and must be used as a means of prevention in areas that have not yet been hit by disaster but are potentially prone to it. The optimisation of techniques aimed at prevention will be one of the basic themes of the development of seismic zoning in the 21st century.

2. SEISMIC ZONING IN THE 20TH CENTURY

2.1 Deterministic method

The first scientific and technical methods developed for zoning were based on the observation that damage distribution is often correlated to the spatial distribution and the physical properties of the underlying terrain and rocks. All the deterministic cartography relating to seismic zoning is based on the empirical determination of ground motion and damage after the occurrence of strong earthquakes. Attention is initially focussed on ground motion and the identification and delineation of terrains whose characteristics would selectively amplify the seismic movement in fairly narrow frequency bands. National- and regional-scale cartography constructed according to these methods therefore depends crucially on what has been observed in the most recent earthquakes. Even though it now receives increasing attention and credit, the development of the deterministic method has been fairly slow, essentially for three reasons: 1) the limited amount of detailed seismic data available, particularly data on ground motion (accelerograms); 2) the lack of knowledge of the fundamental physical processes involved in seismic sources and non-linear soil behaviour; 3) the absence of instruments of numerical analysis to assist in the realistic model-building of seismic wave generation and propagation. Despite these objective difficulties some countries, Japan for example, have made successful use of deterministic zoning maps to reduce seismic hazard. Most countries, however, have usually preferred not to draw up or use seismic zoning maps, presenting these main points in attempts to justify their culpable inaction: a) seismic zoning is a matter for local research, not an internationally-accepted professional practice; b) some of its methods are based on extrapolations of a very limited body of data and are therefore uncertain and unreliable; c) some of its methods are controversial - there is no common consensus among scientists and engineers concerning a standard procedure.

The main stages of deterministic zoning are illustrated in Figure 1 and may be summed up as follows [1]:

the first stage involves the identification and classification of seismic sources (known sources and sources that may be postulated on the basis of geological and physical evidence) and the models they correspond to (point, line, area, volume). In the second stage each source has ascribed to it a typical earthquake, each with its own postulated maximum magnitude. To all the sites included in the zoning it is therefore possible to associate one or more "dominant earthquakes", defined as the most important events in terms of the site's seismic risk. The next stage deals with the identification of the effects

on the site, generally definable in terms of ground motion (displacement, velocity and acceleration). This is usually carried out by means of attenuation laws, deduced from the analysis of experimental data, and in the more advanced methods, by means of computation of realistic synthetic seismograms. This procedure makes it possible, in the case of an event of known magnitude, to estimate ground motion at a given distance from the source. It is often the results obtained at this stage that make it possible to identify each site's "dominant earthquake". The fourth stage, closely depending on the third and sometimes coincident with it, deals with the final definition of site hazard.

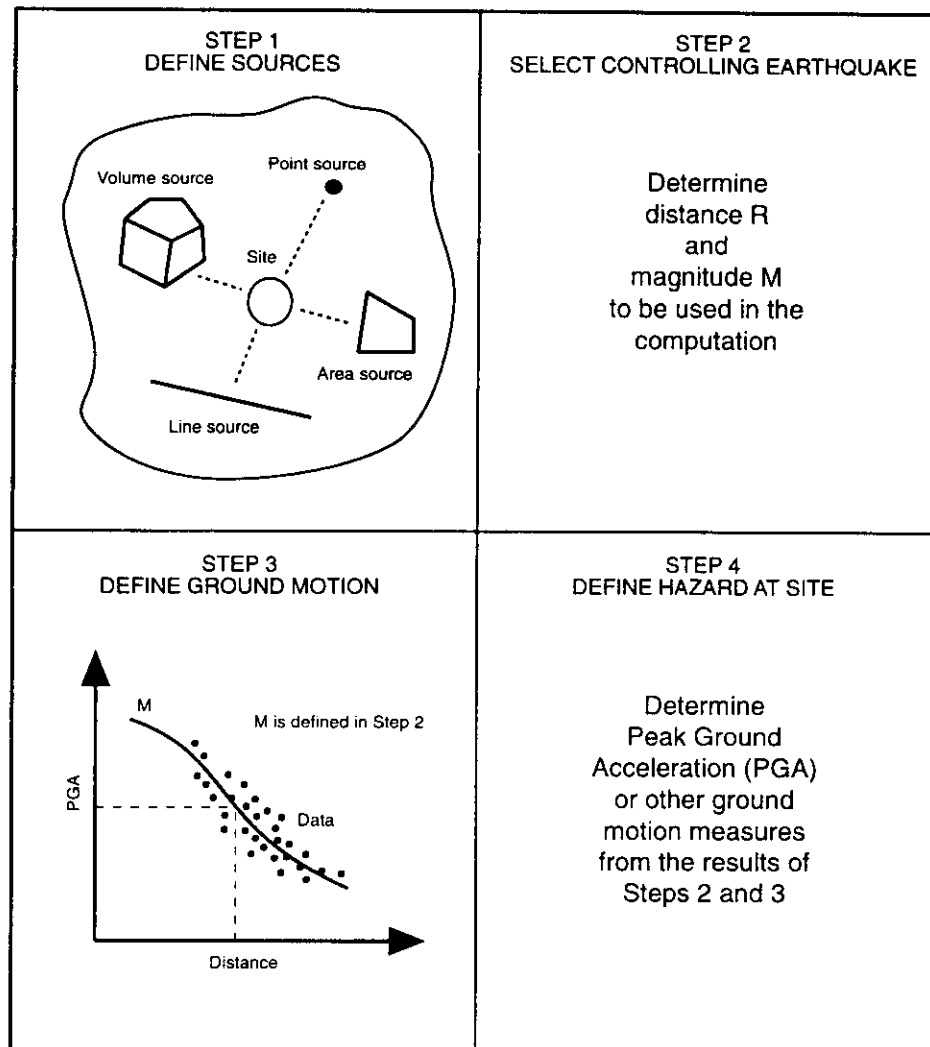


Figure 1. Basic steps of deterministic seismic hazard analysis (modified from [1]).

2.2 Probabilistic method

The 1970s saw the beginning of the construction of probabilistic seismic zoning maps on a national, regional and urban (microzoning) scale. In the 1990s these instruments for the mitigation of seismic hazard are coming to prevail over deterministic cartography. This is the result of five concomitant factors: 1) the remarkable increase in seismic data, particularly relating to ground motion (accelerograms); 2) progress in the study of the physics of seismic sources; 3) progress in seismic energy attenuation models; 4) progress in local amplification models; 5) improvements in uncertainty estimates. Recent destructive earthquakes (Algeria 1980, Chile 1985, Mexico 1985, Armenia 1988, Loma

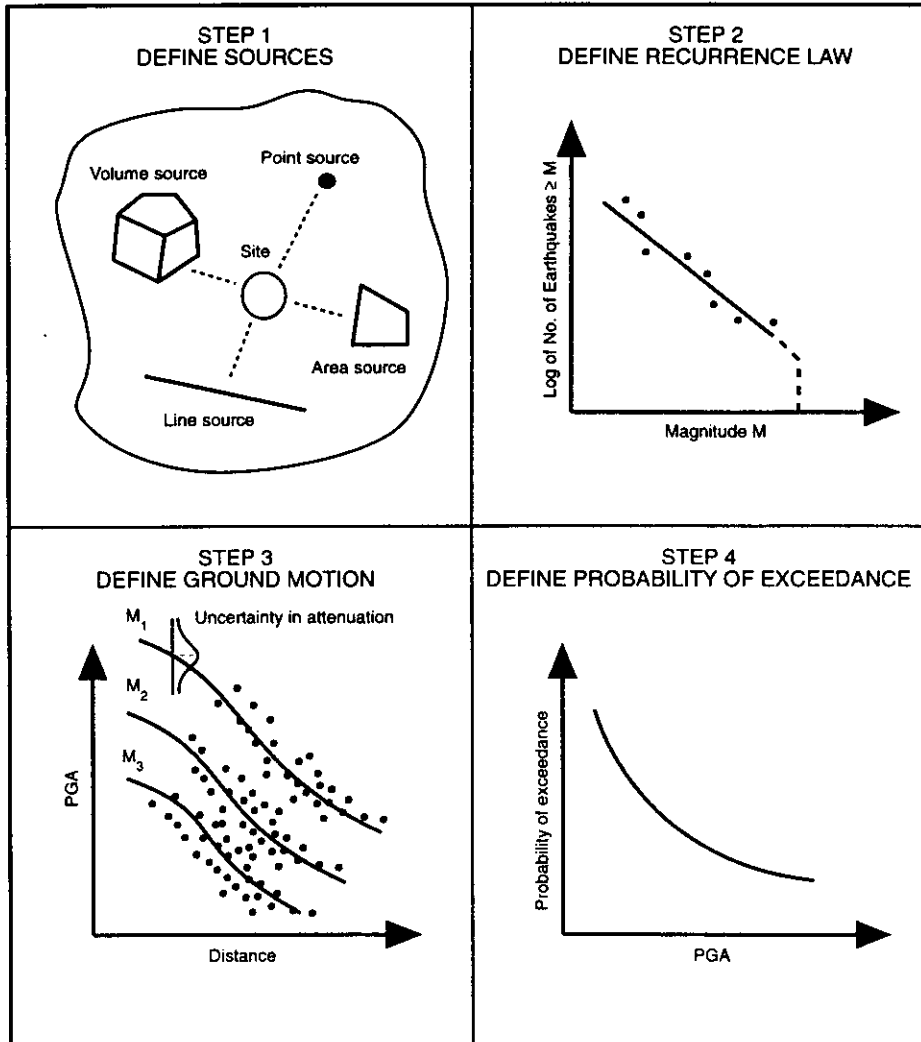


Figure 2. Basic steps of probabilistic seismic hazard analysis (modified from [1]).

Prieta 1989, the Philippines 1990, Costa Rica 1991) have contributed to considerable scientific and technical progress in seismic zoning, emphasising above all the social importance of zoning.

The principal stages of probabilistic zoning are illustrated in Figure 2, and may be summarised as follows [1]:

the first stage is generally similar to what has already been described in the deterministic method, with the difference that the probability of occurrence of a seismic event is the same along the entire seismogenic structure. An upper limit is chosen for the magnitude to be attributed to each source. The law of event recurrence is then defined, source by source, by means of an analysis of seismic history (number of earthquakes observed per class of magnitude). This is markedly different from the corresponding stage of the deterministic approach, in which there is no analysis of a seismic sequence but simply the choice of a single representative event. The third stage is basically similar to the corresponding stage in the deterministic method, with the difference that now a family of attenuation laws is identified, each of which is valid for one class of magnitude. In addition, each curve has attributed to it an estimate of the uncertainty of the attenuation measurement. The fourth stage, involving the estimation of site hazard, differs considerably from the deterministic method. It integrates the effects of all events, irrespective of their magnitude, localisation and probability of occurrence, to obtain a curve showing the probability of exceeding a threshold level for a given ground motion parameter (for example peak acceleration) in a freely-chosen period of time.

In probabilistic analysis it is generally assumed that earthquakes have no "memory", that is to say that each earthquake takes place without knowing that other events have already happened, or will happen in the future, on the same fault. This is known as the Poisson seismic model. As it is clearly not compatible with the observation of foreshocks and aftershocks, it is used only when it is not possible to specify more accurately the physical characteristics of the source by means of a detailed analysis of seismic sequences, deformation release and other forms of spatio-temporal relations that can link individual earthquakes.

2.3 Deterministic method or probabilistic method?

The most controversial question in the definition of standards to be used in the evaluation of seismic hazard may be formulated as follows: should probabilistic or deterministic criteria and methods be used? Although the current trend favours probabilistic methods, the situation is far from clear. In recent years the two approaches have been following each other in and out of favour.

The deterministic method provides seismic hazard estimates which are easily comprehensible and communicable to the user - it is a clear method. The basis of the conclusions are clear to the analysts (seismologists, geologists and geophysicists), the users (engineers and Civil Defence bodies) and everybody involved in problems connected with an area's seismic phenomena. With the deterministic method it is easy to answer questions such as "what difference does it make if the maximum magnitude in a given seismogenic zone increases by a given amount?". The simple chain of clearly-defined data on faults or fault systems, maximum magnitude and ground motion may easily be subjected to complex parametric tests even if the single elements in the chain are determined with extremely sophisticated techniques. The deterministic method also allows the easy inclusion of new information made available after the stage at which the hazard analysis was carried out, which makes it easy to assess the importance of the new data.

On the other hand, unless complex parametric analyses are used it is not possible with the deterministic method to take account of the uncertainties associated with estimates of ground motion and maximum magnitude. It should be observed, however, that the

limitedness of the accelerometric data bank means that knowledge of maximum magnitude is inadequate for zoning purposes. An analysis of accelerometric data from strong earthquakes of a magnitude from 6 to 7 from 1930 to the present day shows that peak acceleration at equal magnitudes may vary by up to 400% [1]. A partial solution to this problem may be obtained by the use of deterministic methods for the formulation of realistic ground motion models, based on knowledge of the elastic and anelastic parameters of the zone in question. Some of these methods, which are described below, will be of cardinal importance in zoning in the 21st century since they make it possible to obtain a highly realistic ground motion estimate, even when the movement differs greatly from what could be extrapolated on the basis of empirically-acquired experience.

The main advantage of the probabilistic method is that it can take immediate account of earthquake frequency and the uncertainties inherent in hazard estimates. This makes it possible to present the results of zoning in terms of annual probability of exceeding a certain level of the peak parameters that characterise ground motion (acceleration, velocity, displacement) and so to compare them with other types of hazard and with socially-acceptable levels of conservatism and risk.

The drawbacks of the probabilistic method stem from the power of the method itself. Its ability to combine great quantities of data, theories and evaluations of varying degrees of objectivity in a final product yields a result that is less clear than is the case with the deterministic method. The result of a probabilistic zoning is usually constituted by the representation of peak acceleration as a function of the annual probability of excess. No indication is generally given as to whether this value is associated with a near event of intermediate magnitude or a more distant event of great magnitude. Even if the peak value is the same in both cases, quantities which are very important for engineers such as spectral levels and durations may differ widely, with obvious consequences. Probabilistic analysis is able to combine geological, geophysical and seismological information so efficiently that the basic causative elements may be unclear even to experts, if the latter were not directly involved in the processing. The probabilistic method is also able to provide numerical results at whatever level of accuracy is initially requested. It should be remembered, however, that at the origin of these results, so rigorously obtained, are data which are often strongly conditioned by *a priori* assumptions, and which therefore may be quantified, in the best possible case, only as orders of magnitude. The expert analyst is aware of this and may therefore put the probabilistic result to proper use. But once they have been produced, probabilistic estimates may also be put to improper uses by people who think that as they are represented by a number or a series of numbers accurate to three decimal places they must reflect a correspondingly accurate measurement of fact.

In conclusion, the deterministic approach provides a method that is clear and verifiable at every stage, a method whose assumptions and elements may be examined individually and in detail. It provides engineers and other users with easily understood scenarios that may be related to the questions under consideration. However, since it uses only a discrete body of control events and it does not make it possible to take formal account of the various uncertainties, it tends to neglect earthquake frequency. The probabilistic approach, on the other hand, is able to combine a great variety of information and assessments and their related uncertainties in a highly flexible framework. Unfortunately this characteristic may conceal key elements that led to certain results, and the quantitative nature of the estimates may lead to a false impression of precision.

At the current level of development in the modelling of seismogenesis and of seismic wave propagation, therefore, the best policy for the future is to combine the advantages offered by both methods, using hybrid or integrated methods.

3. THE ROLE OF THE IDNDR IN THE DEVELOPMENT OF SEISMIC ZONING TECHNIQUES

In the 1990s the IDNDR has led to the formation of worldwide networks of organisations that cooperate on questions of seismic zoning. Studies carried out following the most recent strong earthquakes have proved to be important sources of basic knowledge and have acted as catalysts for the use of zoning in seismic risk management. The impetus for this has come essentially from politicians and administrators particularly interested in rapid reconstruction according to criteria which reduce the probability of a repetition of disasters. To this end, maximum political priority is given to the acquisition of new basic data for the construction of new zoning maps and for the improvement of existing maps. These post-earthquake studies have led to the conclusion that the destruction caused by an earthquake is the result of the interaction of three complex systems: 1) the solid earth system, made up of a) the seismic source, b) the propagation of the seismic waves, c) the geometry and physical conditions of the local geology; 2) the anthropised system, whose most important feature in this context is the quality of

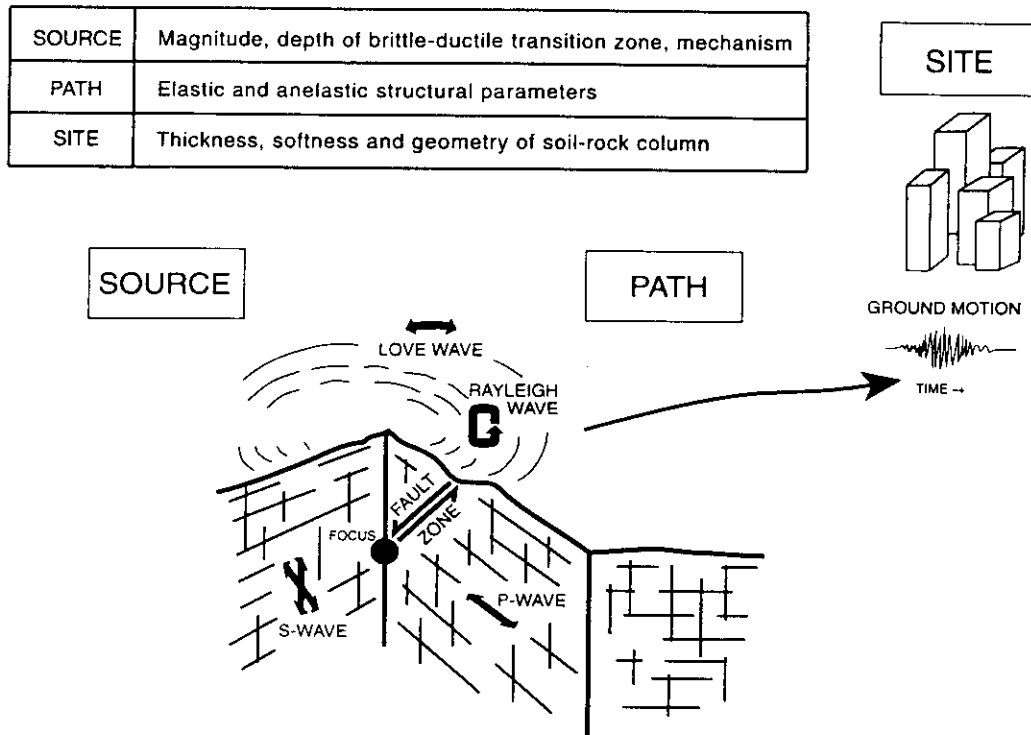


Figure 3. Seismic zoning in the 21st century will be based on integrated scientific databases that will be updated dynamically. Communities will be able to identify the safest locations for buildings and structures on the basis of integrated data on the solid earth system, the built environment and the social economic-political system (modified from [65]).

constructions (buildings, bridges, dams, pipelines, etc.); 3) the social, economic and political system, which governs the use and development of a settlement before it is struck by an earthquake.

The most recent results have shown that in an anthropised area it is now technically possible to identify zones in which, by virtue of physical parameters of source, propagation and local conditions, the most serious damage can be predicted. Concrete examples of this capability, closely linked to the ability to calculate realistic synthetic seismograms, will be illustrated in Section 5.

Therefore the application of seismic zoning is most effective where there is the highest degree of cooperation between urban planners, architects, engineers, geologists, seismologists and Civil Defence bodies with a view to integrating their data banks and experience for the elaboration of a basic urban development plan, and for the identification of realistic criteria and guidelines for the recovery and development of the urban fabric. The construction of realistic seismic zoning maps, integrating the solid land system with the anthropised system and the principal social, economic and political factors, is the necessary basis for the reduction of the loss of human lives, material damage and the disintegration of the fabric of society.

By far the most important contribution of the IDNDR, however, is to have shown that with the knowledge acquired to date a drastic change is required in the orientation of zoning. Zoning must no longer be considered a post-disaster activity. It is necessary to proceed to pre-disaster surveys that can be usefully employed to mitigate the effects of the next earthquake. We cannot confine ourselves to using what has been learned from a catastrophe in the area in which it took place, we must be able to take preventive steps, extending, in a scientifically-acceptable way, results obtained to areas in which no direct experience has yet been gained. An opportunity is offered in this direction by the scientific community's ability to make realistic simulations of the behaviour of the solid earth system through the construction of increasingly realistic synthetic seismograms.

4. SEISMIC ZONING IN THE 21ST CENTURY

In the next century seismic zoning will make considerable use of scientific data banks integrated in an expert system by means of which it will be possible to identify the safest and most suitable areas for urban development, taking account of the complex interaction between the solid earth system, the environmental system and the social, economic and political system (Figure 3). This is a typically interdisciplinary prospect which needs synergic interaction between seismology (study of the release and propagation of seismic energy), geology (identification of the location, configuration and potential of seismic sources), geophysics (identification of seismic sources not detected by geological surveys), history (evaluation of earthquakes that preceded the age of recording instruments - the end of the last century), mathematics (development of algorithms and related computer codes necessary in both the deterministic and probabilistic approaches), geotechnics (estimates of the effects of local terrain conditions on ground motion), structural and mechanical engineering (definition of how risk analysis results are to be parametrised) and sociology (study of the economic and social impact of risk analysis). The construction of an expert system able to integrate these disciplines will make it possible to tackle the problem at its widest level of generality and to maintain the dynamic updating of zoning models made necessary by the acquisition of new data and the development of new model-building methods.

Thanks to the IDNDR the future of seismic zoning seems particularly promising for at

least three reasons: 1) the international cooperation and rapid transfer of knowledge stimulated by the IDNDR itself; 2) interdisciplinary cooperation between scientists, engineers, health workers, planners and Civil Defence bodies for the development and application of expert systems able to integrate empirical knowledge with the most advanced model-building methods; 3) the particular attention that will be devoted to pre-earthquake seismic zoning rather than, as has been essentially the practice to date, to post-earthquake situations. Thus, the state of the art of seismic zoning in the 21st century will include the widespread use of sophisticated numerical techniques and super-computers for the deterministic simulation of ground motion and the effects brought about in urban areas by earthquakes of great magnitude. Three-dimensional models will include faults, the geometry of sedimentary basins and the topography and other physical characteristics of the system required for the evaluation of hazard and risk.

5. EXAMPLES OF DETERMINISTIC ZONING USING SYNTHETIC SEISMOGRAMS

The pilot example of the deterministic approach to seismic zoning, developed at the Institute of Geodesy and Geophysics of the University of Trieste [2] for the whole Italian territory, in the framework of the activities of the GNDT (Gruppo Nazionale per la Difesa dai Terremoti, Consiglio Nazionale delle Ricerche) represents one of the most advanced results in this field and can, at the same time, be used as a starting point for the complete development of a hybrid approach that combines the advantages of the probabilistic and of the deterministic methods, minimising their drawbacks.

Synthetic seismograms are constructed to model ground motion at the sites of interest, using knowledge of the physical process of earthquake generation and wave propagation in realistic media. In first order zoning a database of seismograms covering the area of interest (at a regional scale) is computed, neglecting the effects of lateral heterogeneities. Synthetic seismograms are generated in a very efficient way by the modal summation technique [3, 4], so it becomes possible to perform a detailed parametric analyses at reasonable costs. For example, different source and structural models can be taken into account in order to create a wide range of possible scenarios from which to extract essential information for decision making.

Once the parametric analysis has been performed and the gross features of the seismic hazard have been defined, a more detailed modelling of ground motion, which can take into account the local geological and geotechnical conditions at a specific site of interest, becomes possible using a hybrid approach which combines the modal summation technique with finite differences [5, 6].

5.1 First order zoning of the Italian territory

Starting from the available information on the Earth's structure, seismic sources and the level of seismicity of the investigated area, it is possible to estimate (routinely at frequencies as high as 10 Hz) the Peak Ground Acceleration (PGA) or any other parameter relevant in seismic engineering, which can be extracted from the theoretical accelerations computed using the modal summation technique [3, 4]. This procedure allows us to obtain a realistic estimate of the seismic hazard also in those areas for which scarce (or no) historical or instrumental information is available, and easily to perform the relevant parametric analyses.

To reduce the amount of computations the seismic sources can be grouped into homogeneous seismogenic areas, and for each group the representative focal mechanism can be kept constant. The scalar seismic moment associated with each source is

determined from the analysis of the maximum magnitude observed in the epicentral area. The flow-chart of this procedure is shown in Figure 4.

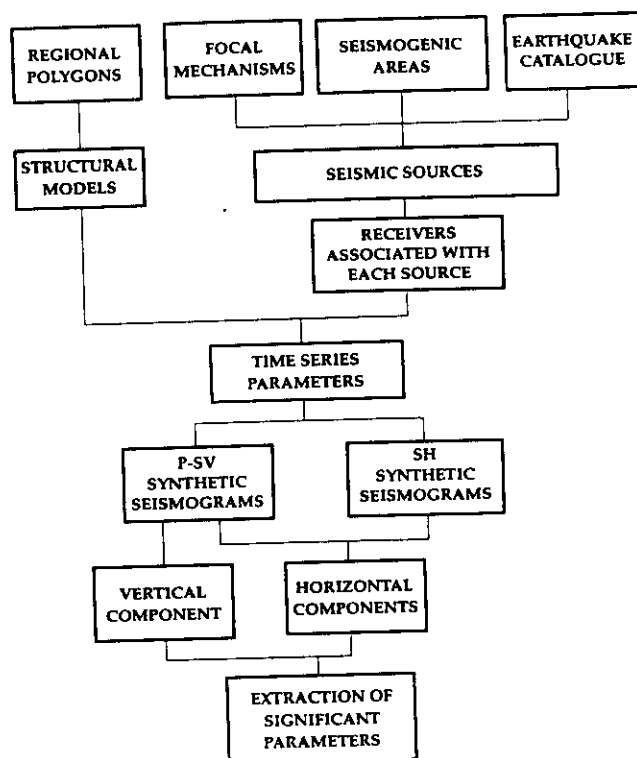


Figure 4. Flow chart describing the procedure for the first order zoning of a territory (from [2]).

5.1.1 Data

On the basis of lithospheric characteristics, the Italian territory has been divided into 16 polygons and a layered structural model has been associated with each polygon. The different layers are described by their thickness, density, P- and S-wave phase velocity and phase attenuation. The crustal layering has been defined taking into account available DSS data [e.g. 7, 8, 9, 10, 11, 12, 13, 14, 15] and indirectly relevant data [e.g. 16], while the lithospheric part of the upper mantle has been modelled using the results obtained by [17].

The spatial distribution of sources covers the seismogenic areas defined by the GNDT [18] on the basis of seismological data and seismotectonic observations [19, 20]. For the definition of the source mechanisms, the available fault-plane solutions grouped in a database [21, 22] have been used.

For the analysis of seismicity, an earthquake catalogue (PFGING) has been prepared, appropriately combining the data from the PFG [23] catalogue for the period 1000-1979 with the data from ING [24] bulletins for the period 1980-1991; only main shocks, shallower than 50 km, have been considered and the aftershocks have been identified with

the algorithm suggested by Keilis-Borok et al. [25].

The earthquakes considered are those that occurred within the PFG polygon [23]. The seismicity may therefore have been underestimated near political borders in the Northern part of Italy, and this could influence the results (PGA distribution) in the regions close to these boundaries. In this respect, the reliability of the results concerning North-Eastern Italy will greatly benefit from possible international cooperation within the Alpe Adria framework, for example.

5.1.2 Computations

To derive the distribution of the maximum observed magnitude over the territory, the image of the seismicity given by the earthquake catalogue was smoothed. At first, the area was subdivided into $0.2^\circ \times 0.2^\circ$ cells. The magnitude value of the most energetic event that occurred within each cell was assigned to it. The smoothing obtained through this discretisation, however, was not found to be satisfactory, since not all cells contain a

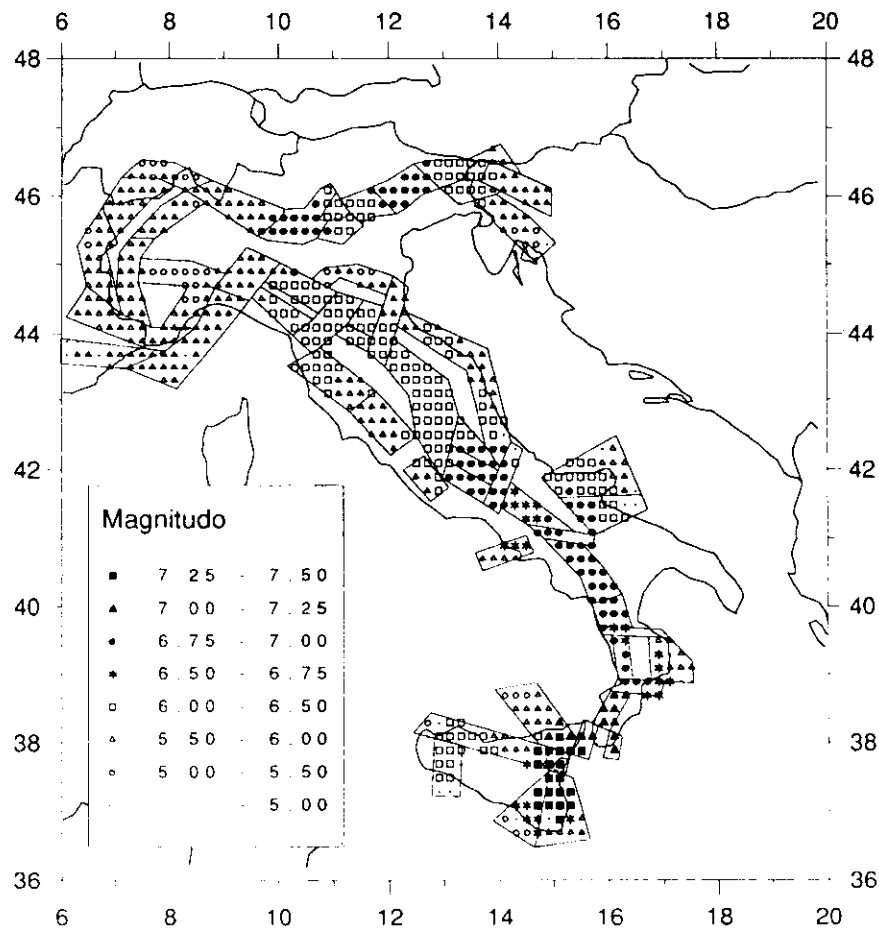


Figure 5. Smoothed magnitude distribution for the cells belonging to the seismicogenic zones defined by GNDT [18] (from [2]).

statistically meaningful number of events. Therefore, the maximum magnitude to be associated with each cell was sought also in the cell surroundings, through the application of a centred smoothing window [26]. For the definition of the seismic sources that are used to generate the synthetic seismograms, only the cells located within a seismogenic area are retained. The map shown in Figure 5 is the result of the application of this method to the PFGING earthquake catalogue.

A seismic source modelled by a double-couple with zero moment is then placed at the centre of each cell. The orientation of the double couple is obtained from the database of the fault-plane solutions. For each seismogenic area, a representative focal mechanism is selected as the arithmetic average of the tensor elements of the available mechanisms. This procedure appears to be reasonable when the mechanisms to average are not too different, and this condition was satisfied for every seismogenic area.

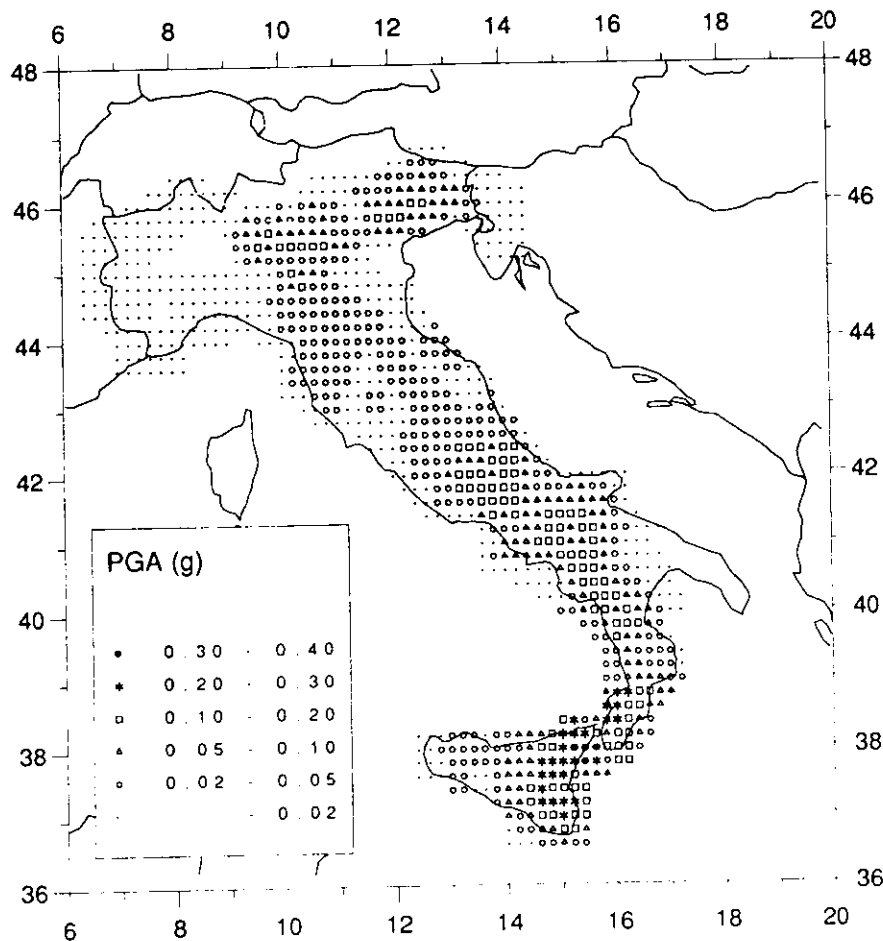


Figure 6. Horizontal PGA distribution for Italy, obtained as a result of the application of the procedure described in Figure 4 (from [2]).

Synthetic seismograms are efficiently computed by the modal summation technique [3, 4] corresponding to a grid ($0.2^\circ \times 0.2^\circ$) covering the whole territory. In this first example, the synthetic signals are computed for an upper frequency limit of 1 Hz, and the point-source approximation is still acceptable. This is fully justified by practical considerations, since for instance several-story buildings have a peak response in the frequency range below 1 Hz [e.g. 27] and by the fact that modern seismic design approaches and technologies, like seismic isolation, tend to lower the oscillations frequencies of buildings. When shorter periods are considered, it is no longer possible to neglect the finite dimensions of the faults and the rupturing process at the source, with the consequent necessity for complete parametric analyses.

All seismograms have been computed for a constant hypocentral depth (10 km), but it is also possible to assign to each source an average depth determined from the analysis of catalogues of past seismicity. The reason for keeping the hypocentral depth fixed and shallow is to be found in the large uncertainties affecting the hypocentral depth contained in the PFGING catalogue, and in the fact that for a given magnitude strong ground motion is mainly controlled by shallow sources [e.g. 28].

P-SV (radial and vertical components) and SH (transverse component) synthetic seismograms are originally computed for a seismic moment of $1 \cdot 10^{-7}$ N m. The amplitudes are then properly scaled according to the (smoothed) magnitude associated with the cell of the source. For the moment-magnitude relation we chose the one given by Boore [29], and to obtain the values which are valid for the cut-off frequency of 1 Hz we used the scaling law proposed by Gusev [30]. The idea, typical of the probabilistic approach, of a constant magnitude within each seismogenic area (choosing the maximum available value) was discarded because for the larger seismogenic areas it leads to an over-estimation of the seismicity, but can be used to establish a conservative upper limit.

At each point of the grid of receivers the horizontal components are first rotated to a reference system common to the whole territory (North-South and East-West directions) and then the vector sum is computed. Among the parameters representative of the strong ground motion we have, for the moment, focused our attention on Peak Ground Acceleration (PGA). Since we compute the complete time series we are not limited to this choice, and it is also possible to consider other parameters, like Arias [31] intensity or other integral quantities that can be of interest in seismic engineering. Since recordings of many different sources are associated to each receiver but one single value is to be plotted on a map (Figure 6), only the maximum value of the analysed parameter is considered.

5.1.3 Check of the results against independent observations

The intensity-acceleration relation proposed by Boschi et al. [32] was used to compare the results of Figure 6 with the historical data, for which only macroseismic intensity estimates exist. In the regions where strong earthquakes occurred we checked that the computed PGA values were compatible with the epicentral intensity, according to the above mentioned relation.

A more quantitative check was made using the observed accelerograms recorded during the Irpinia earthquake on 23 November 1980. It is well known that the source rupturing process of that event was very complex [e.g. 33], and the dimension of the source has been estimated to be of the order of several tens of km. Nevertheless, it seems that the signal recorded at the station of Sturno was mostly due to a single sub-event that occurred rather close to the station itself, while the energy contributions coming from other regions of the source seem unimportant [28]. With the cut-off frequency at 1 Hz, we low-pass filtered the horizontal component accelerograms recorded at Sturno to compare them with our computed signals for the Irpinia region. The example shown in Figure 7 refers to the NS component but the same considerations can be applied to the EW

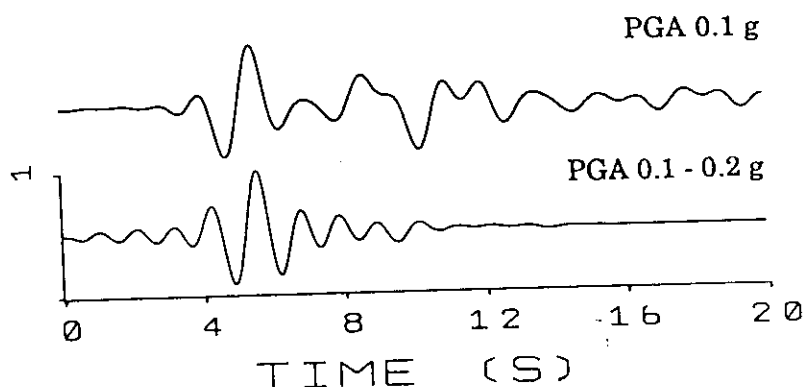


Figure 7. Comparison between NS acceleration recorded at the Sturmo station during the Irpinia earthquake of 23 November, 1980 (above) and one synthetic signal computed for that area (below) on the basis of the procedure described in Section 5.1. Accelerations were low-pass filtered with a cut-off frequency of 1 Hz (from [2]).

component of motion. The early phases and the PGA of the two time series are in very good agreement. The later part of the observed recording is more complicated and this is related to the complexity of the source, which was deliberately neglected in the computation of the synthetic signal.

5.1.4 The Friuli region

In Figure 8 a blow-up of Figure 6 for the Friuli region is presented. It can be seen that the highest PGAs are estimated in the western part of Friuli as a result of the magnitude smoothing used in the procedure. Large PGA values can be estimated in central and Eastern Friuli even neglecting the May 6, 1976 event, as a result of the earthquake that occurred in the Veneto region on June 29, 1873 ($M_K=6.8$). This is a good example of the relevance of our method for the prevention aspects of Civil Defence, connected with the reinforcement of existing buildings and structures.

Of course it is not possible to refine the results obtained with a first order zoning of the whole Italian territory by simply assuming a finer grid of receivers and possibly a higher cut-off frequency (> 1 Hz) in the computation of the synthetic seismograms. A more detailed zoning requires a better knowledge of the seismogenic process in the region. In the specific example of Friuli, seismicity data from the Italian earthquake catalogue should be integrated with what has been collected by the Austrian and Slovenian seismologists. Furthermore, to model wave propagation in greater detail the influence of lateral heterogeneities in the structural model must be taken into account in the computation of synthetic seismograms. The results shown in Figure 8 are the starting point for more accurate investigations, an example of which is described in Section 5.2.1.

5.2 Detailed zoning

Detailed numerical simulations play an important role in the estimation of ground motion in regions of complex geology. In engineering seismology, they can provide synthetic signals for areas where recordings are absent and are therefore very useful for

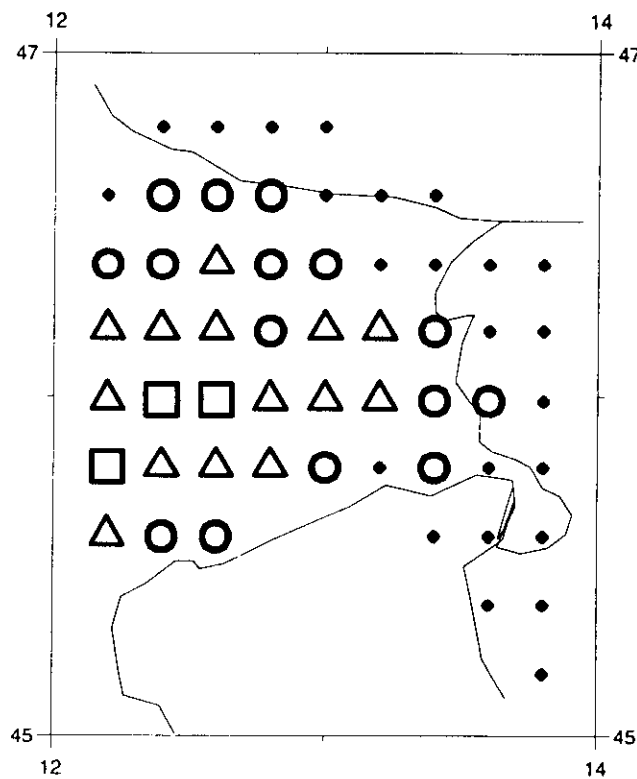


Figure 8. A blow-up of Figure 6 for the Friuli region. The legend of Figure 6 has to be used for the PGA.

the design of earthquake-resistant structures. For applications in seismic prospecting studies, nowadays using high resolution CROP-type surveys [e.g. 34] necessary for the detailed definition of the elastic properties of sub-surface geology, it is generally sufficient to treat wave propagation in laterally heterogeneous structures with asymptotic forms for high frequencies. These methods, called "ray methods", can only be applied to smoothly varying media, where the characteristic dimensions of the inhomogeneities are considerably larger than the prevailing wavelength. They fail, however, to predict ground motion at sites close to lateral heterogeneities such as edges of sedimentary basins and at sites above irregular bedrock-sediment interfaces, where excitation of local surface waves and resonance effects can become important.

Far away from lateral heterogeneities, a local structure can sometimes be approximated by a horizontally-layered structural model, and the mode summation method is the most powerful tool for computing broadband synthetic seismograms. This method is still suitable when lateral variations can be schematized with vertical discontinuities [35], but it is presently not applicable to local irregular structures, which

cannot be reduced to plane-layered models. Since high-frequency seismograms are very sensitive to lateral heterogeneities, the influence of these local and irregular heterogeneities must be included in the numerical modelling. This can be done combining the modal summation and the finite difference techniques [5, 6], thereby avoiding the restriction to asymptotic forms for high frequencies. The method uses each of the two techniques in that part of the structural model where it works most efficiently and permits the calculation of the local wavefield generated by realistic seismic sources at any epicentral distance.

5.2.1 The Friuli region

The hybrid technique can be fruitfully applied to the parametric analysis of the influence of the structural model on the computed ground motion. As reference data for our analysis we considered the records from the three-component station at Buia, one of the nearest accelerographic stations [36] to the September 11, 1976 Friuli aftershock ($16^{\text{h}}35^{\text{m}}04^{\text{s}}$).

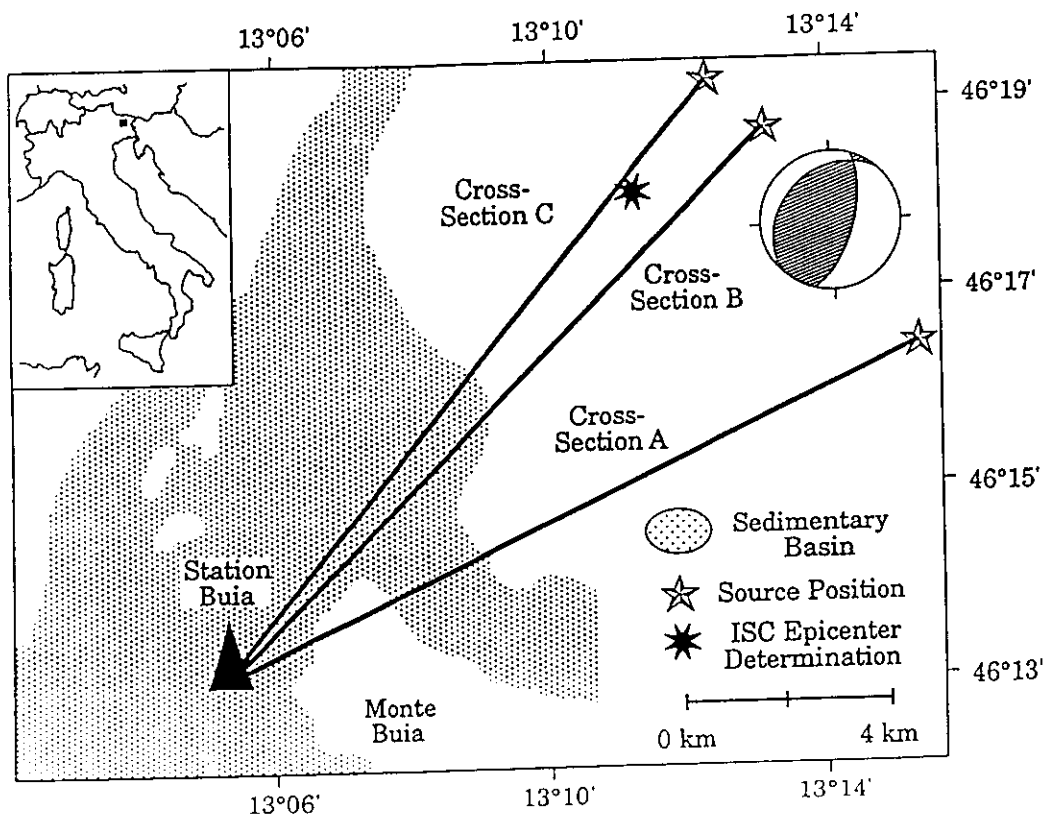


Figure 9. Overview of the Friuli region, outlining the presence of the quaternary basin, the ISC epicenter determination of the 11 September 1976 aftershock and the position of the Buia station. The solid lines indicate the cross-sections considered in the two-dimensional modelling (from [43]).

The area where the station of Buia is placed is characterized by terrigenous sediments (Flysch), widely outcropping at Monte Buia (Figure 9). They are covered locally by a thin quaternary layer, forming a sedimentary basin, and overlap a carbonatic mesozoic sequence. The surface sediments are incoherent, of glacial, alluvial, and lacustrine origin [37]. They form what is known as the Amphitheatre of the Tagliamento river. The thicknesses of the quaternary sediments are well known [38] and locally can reach 100 m. At the Buia station they reach a thickness of about 57 m.

Assuming a one-dimensional, layered, anelastic structural model for the region (model FRIUL7W of Mao and Suhadolc [39, 40]), Panza and Suhadolc [41] and Florsch et al. [4], considering a finite source approximated by a sum of several point-sources, modelling different rupturing episodes, whose orientation agrees well with previously published results by Slejko and Renner [42], reproduced the vertical and EW components of motion observed at the Buia station for the September 11, 1976 earthquake, whereas the synthetic NS-component has excessively large amplitudes in the coda. The difficulty in reproducing the observed horizontal motion with a one-dimensional structural model is

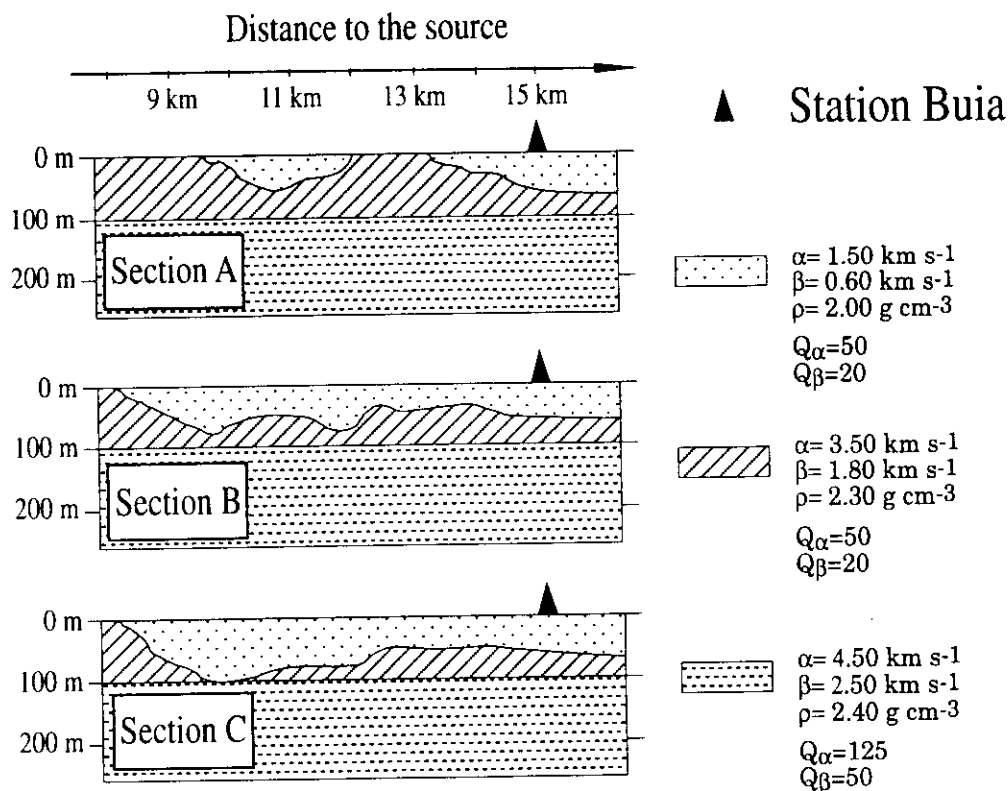


Figure 10. The two-dimensional models corresponding to cross-sections A, B and C of Figure 9 (modified from [43]).

due to the fact that local lateral heterogeneities strongly influence these components. Convincing additional experimental evidence of the different influence of local soil conditions on vertical and horizontal components is represented by the strong motion records that will be discussed in Section 5.2.2.

The effect of the lateral variations was studied [43] using the available data on the depths to the bedrock in the sedimentary basin [38], the seismic P-wave velocities of the quaternary sediments [44, 45] and the variability of shear-wave velocities [46].

The parametric study was made considering wave propagation along different cross-sections. Their positions are shown in Figure 9, and the related two-dimensional structural models are presented in Figure 10. The main features of cross-section A are two sedimentary basins, separated by the outcropping of Flysch at Monte Buia; cross-section B represents an average model for the region and cross-section C represents the part of the Amphitheatre with deep sediments. The layered one-dimensional model, describing the propagation of waves from the source position to the sedimentary basin, was chosen to be

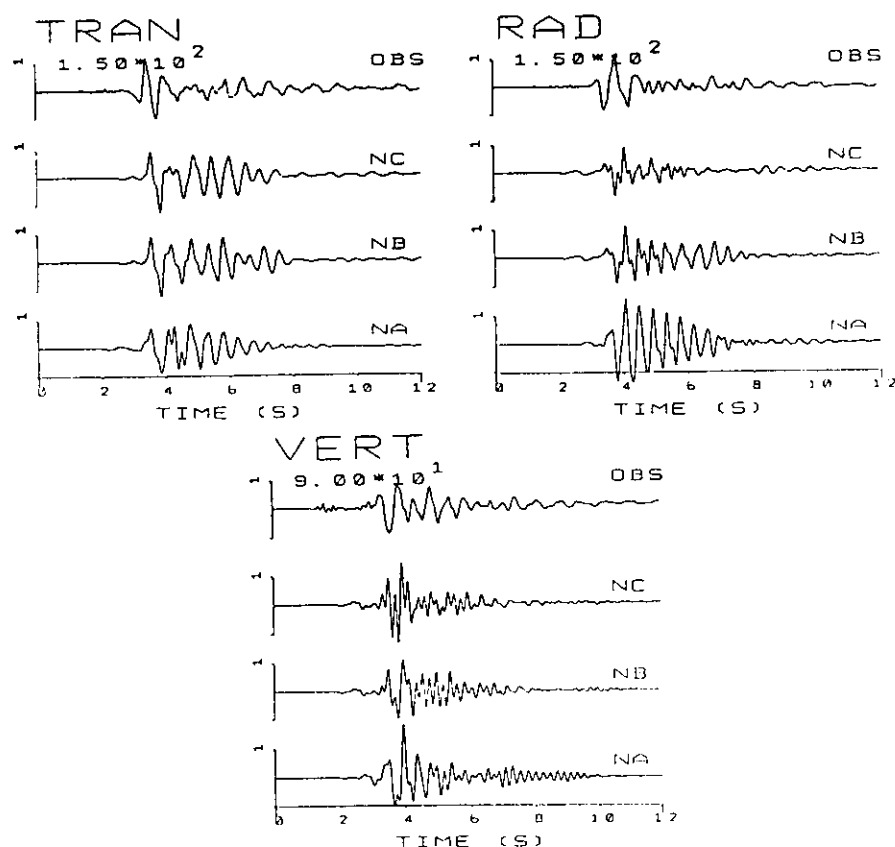


Figure 11. Comparison between the recorded transverse, radial and vertical components of acceleration (OBS) and synthetic signals for the cross-sections C, B and A of Figure 10 (NC, NB and NA respectively) (modified from [43]).

the model FRIUL7W without the original sedimentary cover of 57 m thickness. The source is always placed in the plane of the cross-section, and its depth, mechanism, and duration are those of the first source considered by Florsch et al. [4]. A comparison is shown in Figure 11 between the transverse, radial and vertical components, computed for the three different cross-sections of the basin, and the observed accelerations.

For the transverse component, the local surface waves obtained for cross-sections A, B and C have amplitudes that are too large in comparison with the observed signals. In the choice of the geometry of the bedrock-sediment interface, we restricted ourselves to that given by Giorgetti and Stefanini [38]. However, to reproduce the observed transverse component, the heterogeneities inside the sedimentary basins responsible for the excitation of these local surface waves would have to be different from those used in the numerical modelling. Either the heterogeneities are too close to the Buia station or the bedrock-sediment interfaces are too close to the free surface.

For the radial component of ground motion, the situation with the excitation of local surface waves at the edge of the sedimentary basin, at the places where the bedrock-sediment interface approaches the free surface, and at the outcropping of the bedrock, is not as clear as it is for Love waves. The stronger the lateral heterogeneity within the basin, the greater the amplitudes of the local Rayleigh waves, but at the same time these lateral heterogeneities can reflect most of the local Rayleigh waves coming from the edge of the sedimentary basin closest to the seismic source. To reproduce the observed signal, the lateral heterogeneity within the basin cannot be strong; a strong heterogeneity, would excite large-amplitude local surface waves inside the basin, and these are not observed experimentally.

The comparison between the observed vertical component of ground motion and the synthetic signals shows that for the lower-frequency part (below 4 Hz) there is less difference between the vertical components of motion than is observed for the horizontal ones. The scarce influence of sedimentary basins on the vertical component of motion is a frequently observed fact. A typical example is given by the motion recorded in Mexico City during the 1985 Michoacan earthquake, considered in Section 5.2.2.

The amplitudes of the different components of the synthetic signals agree well with the observations and the synthetic signals can explain their major characteristics. This is an especially important result since it has been possible to model the signals generated by a $M_L=5.7$ earthquake, at relatively high frequencies, assuming a single point-source model.

In general, there is considerable variability in the synthetic ground motion in different realistic two-dimensional structural models. The parametric study shows that waveforms and frequency content of the computed seismograms are sensitive to small changes in the subsurface topography of the sedimentary basin, and in the velocity and quality factor of the sediments. This has also been noted experimentally in records from different sites in existing strong-motion arrays. What remains constant for different realistic structural models is the physical processes that occur within sedimentary basins, e.g., the excitation of local surface waves and resonance effects. The frequency content and dispersion characteristics of the waves induced by these processes are clearly related to the depth of the sediments, the steepness and irregularity of the sediment-bedrock interface and the seismic velocities.

5.2.2 Modelling strong ground motion observed in megacities: Mexico City

Mexico City has experienced extensive damage in the recent past from strong earthquakes with hypocentres in the Mexican subduction zone. The Michoacan earthquake of September 19, 1985 ($M_S=8.1$), together with its aftershocks, produced the worst earthquake damage in the history of Mexico. More than 10,000 people died in Mexico

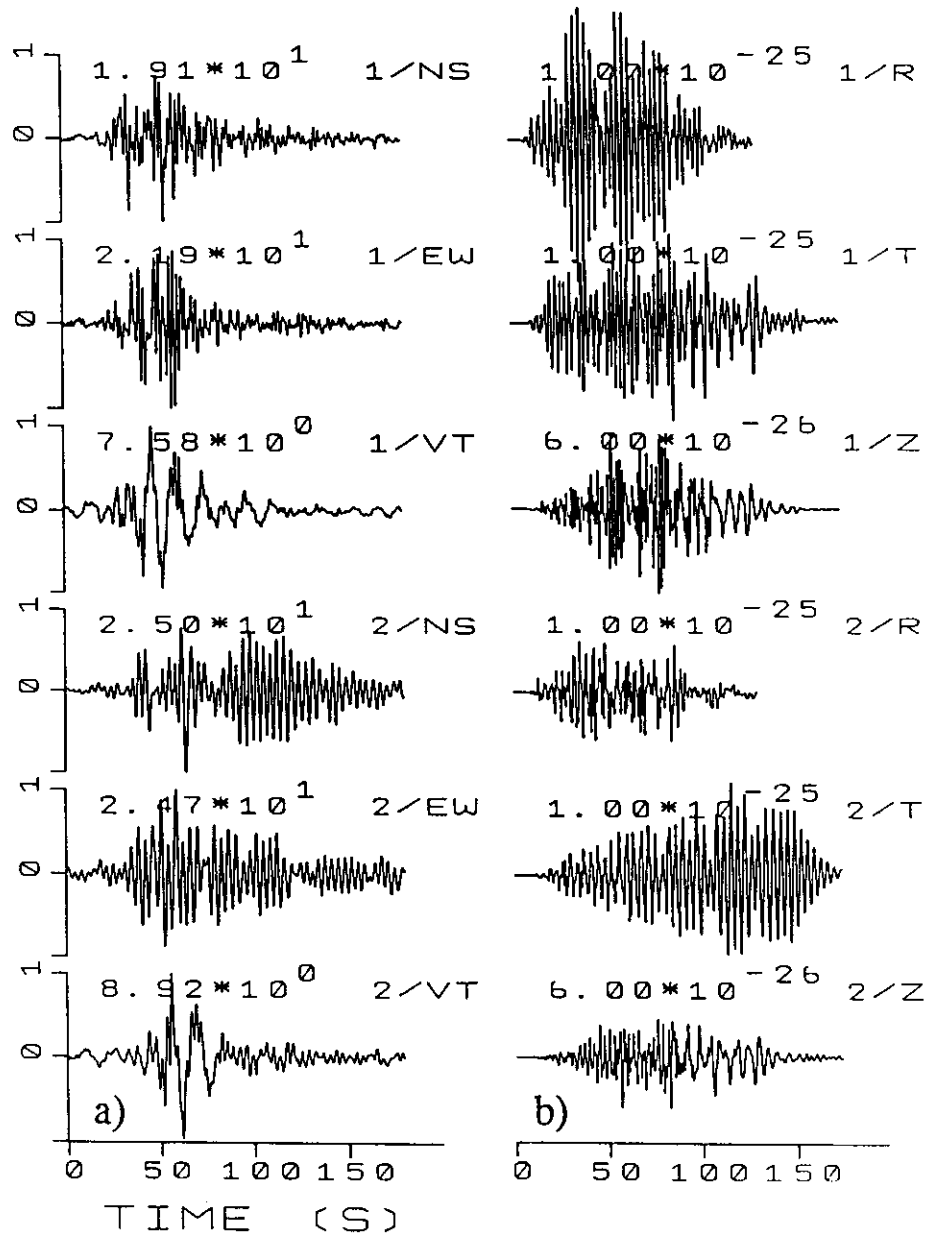


Figure 12. a) Observed horizontal and vertical components of displacements recorded at two stations (1 and 2) in the valley of Mexico City. N denotes the North-South, E the East-West and Z the vertical component.
 b) Synthetic displacements computed with the hybrid technique [5, 6]. R is the radial, T is the transverse component and Z is the vertical component. The signals are normalised, and the peak displacement is indicated in units of cm (modified from [48]).

City, 300,000 people were rendered homeless, and about 1,000 buildings were destroyed [47]. Although the epicentre of the earthquake was close to the Pacific coastline, damage at coastal sites was relatively small. The reason for this is that most of the populated areas near the coast are sited on hard bedrock. In contrast, Mexico City, which is about 400 km from the epicentre, suffered extensive damage. This can be attributed to the geotechnical characteristics of the sediments in the valley of Mexico City.

As the Michoacan earthquake was one of the most precisely-monitored events affecting a large metropolitan area, it is of particular interest to compare observed (Figure 12a) and computed (Figure 12b) strong ground motion.

By studying the one-dimensional response of the two characteristic sedimentary layers present in the Mexico City lake-bed zone, Fäh et al. [48] explained the difference in amplitudes observed between records for receivers inside and outside the lake-bed zone. These simple models show that the sedimentary cover produces the concentration of high-frequency waves (0.2-0.5 Hz) in the horizontal components of motion. The large-amplitude coda of ground motion observed inside the lake-bed zone, and the spectral ratios between signals observed inside and outside the lake-bed zone can only be explained by two-dimensional models of the sedimentary basin [e.g. 49]. In such models, the ground motion is mainly controlled by the response of the uppermost clay layer. The synthetic signals obtained from the numerical modelling [48] reproduce the main characteristics (relative amplitudes, spectral ratios, and frequency content) of the observed ground motion. Teleseismic investigations of the Michoacan-earthquake records yielded a complex rupture process with three subevents [50]; if the energy contributions of these subevents are taken into account the observed duration of ground motion in Mexico City is even better reproduced by synthetic signals.

The area of severe damage in Mexico City is characterized by the increasing thicknesses of the deep sediments and of the clay layer. The large impedance contrast between these two units causes strong resonance effects in the clay layer, as is shown by the computed seismograms (Figure 12b) which are characterized by almost monochromatic wavetrains of long duration and large amplitude in the horizontal components.

The synthetic vertical components of motion do not show any major effect due to the presence of the sedimentary basin. Therefore our calculations give a solid theoretical explanation of wave propagation behaviour often observed in sedimentary basins.

The relation existing between the properties of strong motion records, the geological setting and the distribution of damage in Mexico City widens the spectrum of the possible applications of synthetic seismograms for seismic zoning purposes, allowing the use of earthquakes for which instrumental data are not available (historical events). An example of such possibilities is given in Section 5.2.3.

5.2.3 Modelling damage distribution in megacities: the city of Rome

One benefit of the important historical role of Rome during the last two thousand years is the large quantity of descriptions of earthquakes that have been felt in the city [51, 52]. An important event which caused structural damage in the city of Rome [53] is the January 13, 1915 Fucino earthquake, one of the strongest events that have occurred in Italy during this century (Intensity XI on the MCS scale). The modification of local geotechnical properties in the last 50 years, due to digging, water pumping, and man-made fill, may increase current intensities beyond those observed earlier even if the magnitudes of the future earthquakes do not exceed the historical ones.

The distribution of damage in Rome caused by the Fucino earthquake is well documented. Therefore it is possible to compare the results of a series of different numerical simulations with the observed distribution of damage, using certain quantities

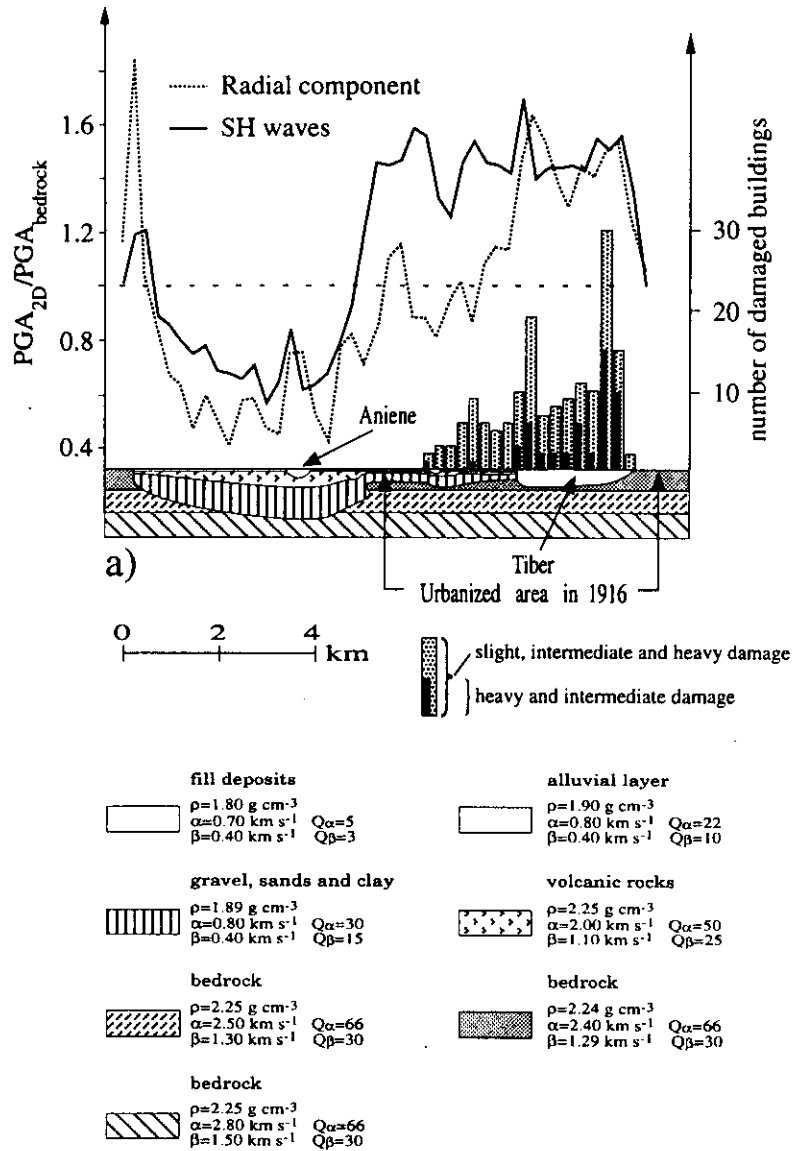


Figure 13a. Ratios of PGA between the results obtained for the two-dimensional and one-dimensional models. They are compared with the damage distribution caused by the January 13, 1915 Fucino earthquake. The two-dimensional structural model used in the computations is also shown (modified from [55]).

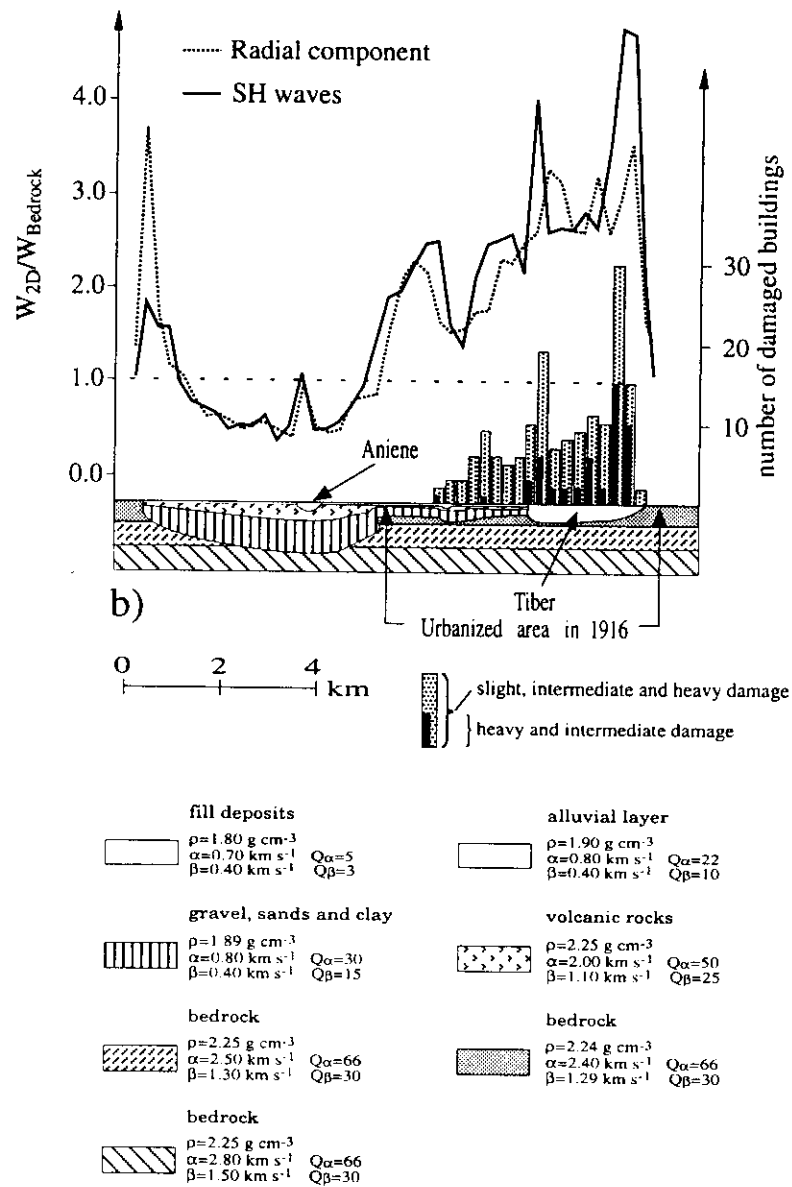


Figure 13b. Ratios of W between the results obtained for the two-dimensional and one-dimensional models. They are compared with the damage distribution caused by the January 13, 1915 Fucino earthquake. The two-dimensional structural model used in the computations is also shown (modified from [55]).

(relevant in seismic engineering) derived from synthetic accelerograms such as PGA and W [54, 55].

For the modelling, the source location and the double-couple orientation proposed by Gasparini et al. [56] were used, and the seismic moment, deduced by Ward and Valensise [57] was properly scaled according to Gusev [30], to be valid for a dominant frequency of 2 Hz. The one-dimensional model describing the path from the source to Rome has been defined by Iodice et al. [54] and is one of the models used in Section 5.1.2.

The two-dimensional structural model for Rome, proposed by Iodice et al. [54], is based on the available geological and geotechnical information [58, 59, 60, 61, 62]. The ancient river bed of the Tiber (referred to as Paleotiber) is composed by clays, sands and gravels (Siciliano). This sedimentary complex is covered by volcanic rocks which have their origin in the volcanic activity in the Pleistocene [58]. The volcanic rocks have greater wave velocities than the underlying sediments (Siciliano), which therefore defines a low-velocity zone. The surficial layer (thickness 10 m) consists of compacted fill and the foundations of man-made structures. The transition from the alluvial sediments in the Tiber and Aniene river beds to the compacted clay (hereafter referred to as bedrock) is characterized by a very high impedance contrast (see Figure 13).

To evaluate the local site effects, it is best to eliminate the source effect and the regional trend. This can be done by calculating the ratios between the values obtained for the two-dimensional model and those determined for a one-dimensional reference model.

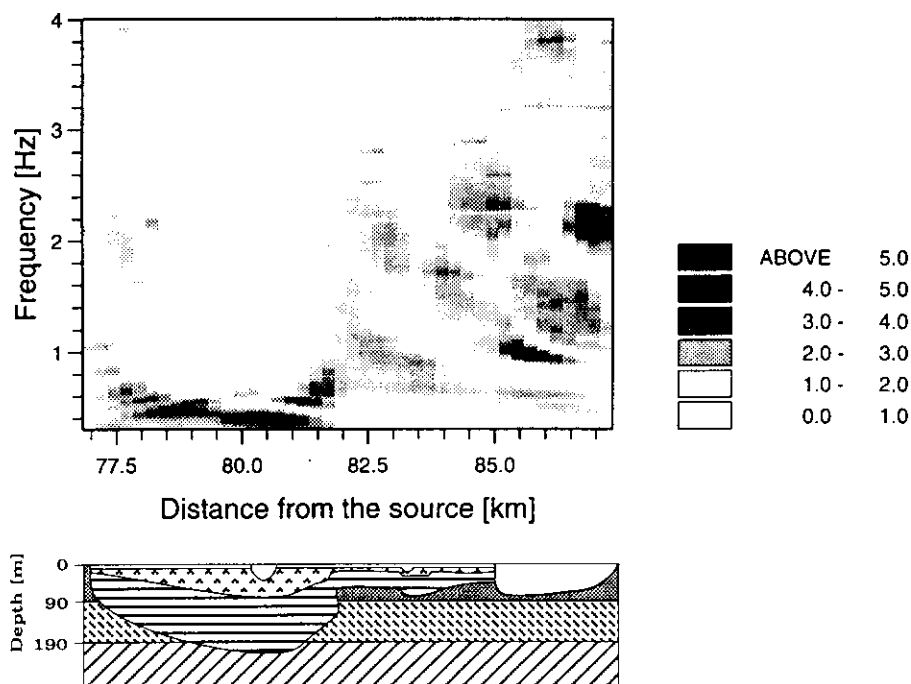


Figure 14. Spectral ratios for transverse accelerations over the cross-section shown in Figure 13 (from [55]).

Since damage is caused mainly by the horizontal components of motion, these ratios are computed for the SH wavefield (transverse component) and for the radial component of the P-SV wavefield. The quantities shown in Figure 13 are (a) PGA and (b) W, relative to the one-dimensional reference model.

The approximate limits of the area of urbanization in 1916 are indicated by two arrows in Figure 13. These damage statistics have been defined in Fäh et al. [55] and should be interpreted only in a qualitative manner, as neither the type of buildings nor the density of urbanization could be taken into account. In spite of all these limitations, the two peaks at the edges of the alluvial basin of the Tiber and the concentration of the heavy and intermediate damage in this basin are quite clear.

High relative PGAs are observed where the impedance of the surficial sediments is small whereas relative PGAs are low where the volcanic layer is thick. An even better correlation with the observed damage is obtained using the relative W curves. There are four peaks in the relative W curve: at the edges of the Tiber basin, within the alluvial valley of the Aniene, and a broad peak at the end of the Siciliano low-velocity zone. Since the correlation is very good between PGA, W and the damage statistics, it is possible to extend the zoning to the entire area of Rome, thus providing a basis for the prediction of the expected damage from a future strong Apenninic event.

Another possible representation of two-dimensional effects is given by the computation of spectral ratios between the two-dimensional and the one-dimensional signals from the same site [55]. The result for the transverse component, plotted as a function of frequency and spatial location along the section, is shown in Figure 14. The darker an area, the stronger the amplifications that characterize the two-dimensional model with respect to its one-dimensional analogue. The greatest amplification (5-6 times) is observed at the western edge of the sedimentary basin of the Tiber river (87 km from the source), for frequencies around 2 Hz, and it is due to the combination of resonance effects with the excitation of local surface waves.

6. CONCLUSIONS

The traditional deterministic methods of first order seismic zoning have the main disadvantage of neglecting the existing models of earthquake sources and realistic wave propagation, and are generally based upon some empirical attenuation laws of seismic energy with distance. Such attenuation laws do not take properly into account the effects of structural irregularities that could heavily amplify the horizontal components of ground motion, as was shown, for example, in the cases of Mexico City and Rome. As a consequence, traditional deterministic methods can only lead to a kind of "post-event" zoning whose validity cannot be easily extrapolated in time and to different regions and which therefore must be considered obsolete.

On the contrary the method described here, being based on the computation of realistic synthetic seismograms, makes it possible to take source and propagation effects into account. Therefore, a huge amount of geological and geotechnical data, already available, can be fully utilised. The results obtained for Mexico City show that even an approximate knowledge of the mechanical properties of the soil is sufficient to give a realistic estimate of ground motion.

Because of its flexibility, the method is highly suitable for inclusion in some new integrated procedures, a kind of compromise between probabilistic and deterministic approaches, that can be developed in order to minimize the drawbacks of each method. For example, one way to integration is to assign a probability to the results of the

deterministic approach. One can be interested in evaluating the hazard due either to one single earthquake with a low probability of occurrence, or to more frequent events of lower magnitude, therefore the maximum magnitude used in the deterministic approach must be the one associated with a specified recurrence curve and an annual probability of occurrence.

It may happen that the results obtained with the standard deterministic methods are no longer valid when a new strong earthquake occurs. With our approach, as is shown in the case of Friuli in Section 5.1.4, this shortcoming is very probably eliminated, or at least drastically reduced, by the smoothing that is performed in the preliminary stage of the seismicity analysis.

The ability to estimate accurately seismic hazard at very low probability of exceedance may be important in protecting dams or power plants against rare earthquakes. Our deterministic approach, based upon the assumption that several earthquakes can occur within a predefined seismic zone, represents a conservative definition of seismic hazard for pre-event localized planning for disaster mitigation.

If the seismotectonic regime is sufficiently well known, post-event synthetic isoseismals for the source regions can be drawn [63]. This capability has strong implications in post-event emergency management, as it can direct the intervention of the Civil Defence to where the strongest damage is most likely to have occurred.

One aspect which is not included in the discussion of the microzoning of selected areas is the influence of surface topography on ground motion. This approximation can be justified for sites inside sedimentary basins, where topographic features are generally small. However, topography can become important at the edges of sedimentary basins, especially in mountainous regions such as the Friuli area, and is now included in the numerical scheme [64].

The detailed modelling of ground motion for realistic two-dimensional media is a particularly powerful tool for the prevention aspects of Civil Defence. With the method described, it is possible to obtain, at low cost and exploiting large quantities of already existing data (e.g. geotechnical parameters, surface geology data, seismological data), the definition of realistic seismic input to structures of interest as the result of the computation of a wide set of time histories and spectral information corresponding to possible seismotectonic scenarios for different source and structural models. Such a data set can be very fruitfully used by civil engineers in the design of new seismo-resistant constructions and in the reinforcement of the existing structures.

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