by G. F. Panza^{1,2}, F. Vaccari^{1,3}, and F. Romanelli^{1,3}

IGCP Project 414: Realistic Modeling of Seismic Input for Megacities and Large Urban Areas

¹ Dipartimento di Scienze della Terra - Università di Trieste, Via Weiss, 4 34127 Trieste, Italy. Fax: +39-40-6762111, Tel: +39-40-6762117,

E-mail: <Panza@geosun0.univ.trieste.it>.

² The Abdus Salam International Centre for Theoretical Physics, Miramar, Italy.

³ Gruppo Nazionale per la Difesa dai Terremoti - CNR, Rome, Italy.

The project addresses the problem of pre-disaster orientation: hazard prediction, risk assessment, and hazard mapping, in connection with seismic activity and man-induced vibrations. The definition of realistic seismic input can be obtained from the computation of a wide set of time histories and spectral information, corresponding to possible seismotectonic scenarios for different source and structural models. The availability of realistic numerical simulations enables us to estimate the amplification effects in complex structures exploiting the available geotechnical, lithological, geophysical parameters, topography of the medium, tectonic, historical, palaeoseismological data, and seismotectonic models. The realistic modeling of the ground motion is a very important base of knowledge for the preparation of groundshaking scenarios that represent a valid and economic tool for seismic microzonation. This knowledge can be very fruitfully used by civil engineers in the design of new seismo-resistant constructions and in the reinforcement of the existing built environment, and, therefore, supplies a particularly powerful tool for the prevention aspects of Civil Defense. At present, the project is active in Antananarivo, Bangalore, Beijing, Bucharest, Budapest, Cairo, Catania, Damascus, Delhi, Kathmandu, Ljubljana, Mexicali, Mexico City, Naples, Rome, Santiago de Chile, Santiago de Cuba, Silistra, Sofia, Thessaloniki, Tijuana and Zagreb.

Introduction

The IUGS-UNESCO IGCP Project 414 "Seismic Ground Motion in Large Urban Areas", started in 1997, addresses the problem of pre-disaster orientation: hazard prediction, risk assessment, and hazard mapping, in connection with seismic activity and man-induced vibrations. The major scientific problem is to handle realistic models on a very detailed level. This can now be done by making use of global observations from digital networks, application of modern theories for the forward and the inverse problems, and by the use of very powerful computers.

We can reduce loss of life and property damage by highly detailed, specific prediction of seismic ground motion. With the knowledge of accurate, three-dimensional structures and probable, complex source mechanisms, the detailed ground motion at any site, or all sites of interest, can be determined. To map seismic ground motion we do not have to wait for earthquakes to occur in likely focal regions and then to measure ground motion with an extremely dense set of recording instruments; instead, with the knowledge above we can compute these seismograms from theoretical considerations. Thus, a complete database for all sites and predicted focal mechanisms can be constructed immediately; no delay is necessary while we wait for experimental evidence and recordings. This database would then, naturally, be updated continuously by comparison with incoming new experimental data.

The general plan includes the following large urban areas and megacities: Antananarivo, Bangalore, Beijing, Bucharest, Budapest, Cairo, Catania, Damascus, Delhi, Kathmandu, Ljubljana, Mexicali, Mexico City, Naples, Rome, Santiago de Chile, Santiago de Cuba, Silistra, Sofia, Thessaloniki, Tijuana and Zagreb. This choice is representative of a broad spectrum of seismic hazard levels that require different efforts to reach a satisfactory level of preparedness. We have deliberately chosen objects not situated very close to known seismogenic zones. In fact, the condition of being some tens of kilometers from the epicenter can allow us an optimum exploitation of the results of microzoning, and fill in a gap in preparedness, since, usually, most of the attention is focused on very near seismogenic zones.

At present, the international and interdisciplinary working group is composed by: Prof. E. Paskaleva, Dr. M. Kouteva, Central Laboratory for Seismic Mechanics & Earthquake Engineering, Sofia; Dr. D. Slavov, University of Sofia, Department of Meteorology and Geophysics, Sofia, BULGARIA; Prof. R. Saragoni, Departamento de Ingenieria Civil, Universidad de Chile, Santiago, CHILE; Prof. Y. T. Chen, Dr. Z. Ding, Institute of Geophysics, China Seismological Bureau, Beijing, Dr. R. Sun, Institute of Geophysics, Science Academy of China, Beijing, CHINA; Prof. M. Herak, Dr. I. Lokmer, Geophysical Institute, University of Zagreb, CROATIA; Prof. J. L. Alvarez Gomez, Centro Nacional de Investigaciones Sismologicas, Havana, CUBA; Dr. A. El-Sayed, Geology Department, Mansoura University, Mansoura, EGYPT; Prof. P. Varga, Dr. T. Ziros, Dr. P. Monus, Geodetic and Geophysical Research Institute, Sopron, HUNGARY; Prof. V. Gaur, Indian Institute of Astrophysics, Bangalore, Prof. R. N. Iyengar, Dr. S. K. Agrawal, Central Building Research Institute, Roorkee, INDIA; Prof. G. F. Panza, Prof. P. Suhadolc, Dr. F. Vaccari, Dr. F. Romanelli, Dr. F. Marrara, Dr. A. Sarao', Dr. A. Aoudia, Dipartimento di Scienze della Terra, Università di Trieste and International Center for Theoretical Physics, Trieste; Prof. C. Nunziata, Dr. M. Natale, Dr. R. Mele, Dr. A. Sica, Dipartimento di Geofisica e Vulcanologia, University of Naples; Prof. L. Tortorici, Dipartimento di

Scienze Geologiche, University of Catania, ITALY; Prof. G. Ram-bolamanana, Institut et Observatoire Géophysique d'Antananarivo, Antananarivo, MADAGASCAR; Dr. J. Frez, Centro de Investigación Científica y de Educación Superior de Ensenada, MEXICO; Prof. G. Marmureanu, Dr. M. Radulian, Dr. C. Moldoveanu, Dr. C. Cioflan, Dr. D. Bratosin, Dr. B. Apostol, National Institute for Earth Physics, Bucharest, ROMANIA; Prof. Acad. V. I. Keilis-Borok, Dr. A. Soloviov, Dr. I. Kuznetsov, Dr. I. Rotwain, Dr. G. Molchan,

International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Academy of Sciences, Moscow, RUSSIA; Dr. M. Zivcic, Dr. A. Gosar, Slovenian Association for Geodesy and Geophysics, Geophysical Survey of Slovenia, Ljubljana, SLOVENIA; Dr. H. Abou Roumieh, Dr. A. Hariri, Syrian National Seismic Network, Damascus, SYRIA.

Method

The mapping of the seismic ground motion due to the earthquakes originating in a given seismogenic zone can be made by measuring seismic signals with a dense set of recording instruments when a strong earthquake occurs or/and by computing theoretical signals, using the available information about tectonic and geological/geotechnical properties of the medium, where seismic waves propagate. Strong earthquakes are very rare phenomena and this makes very difficult (practically impossible in the near future) the preparation of a sufficiently large database of recorded strong motion signals that could be analyzed in order to define generally valid ground parameters, to be used in seismic hazard estimations.

While waiting for the increment of the strong motion data set, a very useful approach to perform immediate microzonation is the development and use of modeling tools based, on one hand, on the theoretical knowledge of the physics of the seismic source and of wave propagation and, on the other hand, exploiting the rich database about the geotechnical, geological, tectonic, seismotectonic, historical information already available.

The initial stage of our work requires the collection of all available data concerning the shallow geology, and the construction of cross-sections along which to model the ground motion. This work is by its nature multidisciplinary since information is requested from different disciplines as seismology, history, archaeology, geology and geophysics to give engineers reliable building codes. The realistic modeling of ground motion requires, in fact, the simultaneous knowledge of the geotechnical, lithological, geophysical parameters and topography of the medium, on one side, and tectonic, historical, paleoseismological, seismotectonic models, on the other, for the best possible definition of the probable seismic source. In addition, the use of sophisticated computer modeling of wave propagation in heterogeneous anelastic media allows us the best possible exploitation of the existing information on structures and sources. Different advanced methods and approaches, some of them developed and implemented by partners of this project, are used with the goal of determining different indicators of seismic hazard (e.g. Panza et al., 1996).

At the end of the project, maps of various seismic hazard parameters directly measured or numerically modeled, such as peak ground acceleration, and others of practical use for the design of earthquake-safe structures will be produced, taking advantage of modern GIS technology.

The ongoing activity

The methods used for the modeling of the ground motion are described in detail by Panza (1985), Vaccari et al. (1989), Fäh (1991), Florsch et al. (1991), Fäh et al. (1993), Panza (1993), Fäh et al. (1994), Fäh and Panza (1994) and Romanelli et al. (1996), and permit to take into account in a realistic way source, path and local soil effects on the entire wave train. The results obtained so far are all characterized by a large international co-operation and can be divided into two main groups: (1) Urban areas where data collection is still in progress and the modeling is in the preliminary stage; (2) Urban areas

Figure 1 Relative maximum amplitude (A_{2D}/A_{1D}) and total energy of ground motion (W_{2D}/W_{1D}) along a profile across the Xiji Langfu depression, in Beijing area. The thick low velocity deposits are responsible for the large increment of the values inside the basin. On the two sides of the Xiadian fault, A_{2D}/A_{1D} and W_{2D}/W_{1D} can vary by more than 160% and 600%, respectively. The two different geometries of the sedimentary basin are shown in the lower part of the figure, a) deep basin; b) shallow basin. With the existing relationships between acceleration and macroseismic intensity (I) these results can explain the large values of I observed in the Xiji-Langfu area, in connection with the Tangshan 1976 earthquake (from Sun et al., 1998).

Figure 2 Recorded ground motion in Bucharest (Magurele station) and simulated signal by Moldoveanu and Panza (1998), for periods greater than 1 s, for the event of May 30, 1990.

where the numerical modeling is quite advanced and successfully compared with available observations.

Because of the lack of records, the study of the ground motion in Budapest due to the 1956 Dunaharaszti earthquake, located at about 20 km from the Capital, is based mainly on modeling, using all available information about geological and geotechnical properties. This case represents a typical situation in which the realistic modeling of ground motion is the only tool that permits to estimate the hazard before another event strikes the city.

The ground motion recorded in Mexico City valley during distant earthquakes is often used to illustrate the applicability of the 1-D model with vertically propagating shear waves. However, the analysis of ground displacement waveforms in stations located on firm soil shows that ground displacements are always strongly influenced by Rayleigh waves, with a broad frequency band between 0.08 to 1.0 Hz. No important incident body waves or basin waves are observed (Gomez Bernal and Saragoni, 1997a, b). Therefore, these surface waves greatly contribute to the destructive effects of earthquakes as their frequencies coincide with the site periods encountered at the lake-bed zone (1.0–5.0 s).

In Santiago del Chile, the analysis of the accelerograms recorded for the MS=7.8 Central Chile 1985 earthquake shows ground displacements with important retrograde Rayleigh waves, with strong coupling between horizontal and vertical motion. The study shows that these waves come from the epicenter and from other two sources (Saragoni and Lobos, 1998).

For the microzonation of Santiago de Cuba the initial phase of data collection about the regional crust-upper mantle structure and Santiago de Cuba basin structure has been completed, and the modeling phase just begun.

The site of the city of Sofia falls in the so-called Sofia seismic zone. The main seismogenic zones with influence on the seismic hazard of the Sofia site are: Kresna, Plovdiv, Negotinska Krayna. Vrancea source is located 320 km far from Sofia. The macroseismic effect of Vrancea earthquakes observed on the site of Sofia in 1940 and 1977 correspond to MSK intensities between V and VI. The preliminary results of the deterministic modeling of ground motion for local destructive earthquakes suggest that a reinterpretation of the available studies on the specific attenuation for Sofia Valley is necessary, and that, in the town, the expected intensity may vary between VII and X.

In India, as introductory activity to the microzonation of some Indian megacities, preliminary modeling has been made, taking the Garhwal region of the central sector of Himalaya as an example to carry out seismic microzonation studies for local conditions. Here the 260 m-high earth and rockfill Tehri Dam, across Bhagirathi river, exposes the whole downstream population to high risks. It is, therefore, quite natural, from a socio-economic and scientific point of view, to be speculative about the seismic safety of the dam and its paraphernalia, undertaking a seismic microzonation study for this region. The first preliminary results so far obtained show that, for the Uttarkashi region, despite of the scarce information about the earth crust structure of the area, the comparison of the modeled seismic ground motion with observations is quite satisfactory and realistic (Agrawal, 1998, personal communication), and therefore it is reasonable to extend the seismic microzonation procedure to Indian megacities.

In Naples, the ground motion due to earthquakes occurred in Southern Apennines, with special attention to the November 23, 1980 (MS=6.9, ML=6.5) event, is studied. A quite successful comparison with the strong motion recorded at Torre del Greco has been obtained (Nunziata et al., 1997). In the area studied in detail, the sub-soil 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 very detailed information available about the sub-soil mechanical properties and its geometry gives a very good opportunity to compare the results that can be obtained with standard 1-D techniques (Method 1), based on the vertical propagation of waves in a plane layered structure (e.g. computer program Shake, developed by Schnabel et al., 1972) and with our realistic hybrid technique (Method 2). The discrepancies evidenced between the 1-D and the 2-D seismic responses, suggest that serious caution must be taken in the formulation of seismic regulations (Nunziata et al., 1997). As expected, the sedimentary cover causes an increase of the signal's amplitudes and duration. If a thin uniform peat layer is present at depth, the amplification effects at the free surface are reduced, and the peak ground accelerations are similar to those observed for the bedrock model. The study of the effects of the interaction between soil properties and foundations has shown that the peat layer present in a part of the city can act as a seismic isolator (Nunziata et al., 1997).

The study of the ground motion in Beijing area due to earthquakes occurred in its surroundings, such as the Ms=7.8 Tangshan earthquake of July 28, 1976, about 160 km from the City of Beijing, has given satisfactory comparison with observed macroseismic data, especially in Dachang depression (Sun et al., 1998). The special geological conditions in the Xiji-Langfu area are the main reason for the anomalously high macroseismic intensity caused by the Tangshan 1976 earthquake. The area is formed by deep deposits — mainly alluvium sands and clays poorly consolidated and with high water content — that have been trapped by the Xiadian fault.

From the simulated ground motion, quantities commonly used for engineering purposes, like the maximum amplitude (AMAX) and the total energy of ground motion (W), which is related to the Arias Intensity (Arias, 1970), can be computed. The thick low velocity deposits are responsible for the large increment of the values of AMAX and W inside the basin. On the two sides of the Xiadian fault the relative values of AMAX and W, A2D/A1D and W2D/W1D, can vary by more than 160% and 600% respectively, and these variations

are relatively stable with varying thickness of the sedimentary deposit used in the models, as shown in Figure 1. A2D and W2D represent the values computed for the model containing the sedimentary basins, which are shown at the bottom of the figure, while A1D and W1D represent the same quantities computed for the reference bedrock model given by Sun et al. (1998). With the existing relationships between acceleration and macroseismic intensity I (Medvedev, 1977; Panza et al., 1998), these results can explain the large values of I observed in the Xiji-Langfu area, in connection with the Tangshan earthquake.

Macroseismic effects similar to the ones observed in the Dachang depression are predicted by the modeling in the Beijing depression, not much urbanized at the time of the Tangshan event (Ding et al., 1997). This result represents a very good example of the possibility to produce important information for seismic risk mitigation using what is available now and to improve scenarios as new data become available. To further check the modeling, it is now in progress the analysis of the records of the January 10, 1998 earthquake with $M_s=6.1$, occurred in Zhangbei, Hebei Province, about 180 km NW of Beijing.

The Vrancea seismoactive region, characterized by intermediate-depth earthquakes, is the main quake source that has to be taken into account for the microzonation of Bucharest, that could suffer serious damage because of the severe local site effects. The strong seismic events originating in Vrancea have caused the most destructive effects experienced on the Romanian territory. Since about four destructive earthquakes occur every century in Vrancea, the microzonation of Bucharest, exposed to the potential damages due to these strong intermediate-depth shocks, is an essential step toward the mitigation of the local seismic risk.

The study of ground motion in Bucharest, due to earthquakes occurred in Vrancea, has been focused on the May 30, 1990, $M_w=6.9$ event. Moldoveanu and Panza (1998) succeeded in reproducing, for periods greater than 1 second, the recorded ground motion in Bucharest (Magurele station), at a very satisfactory level for seismic engineering, even if a relatively simple local structure and seismic source have been considered (Figure 2). All the three components of motion are influenced by the presence of the deep alluvial sediments, the strongest local effect being visible (both observed and computed) in the transversal (T) one. Parametric tests, that represent a major advantage of the numerical simulations, have been performed considering the two fault plane solutions representative of the major Vrancea intermediate-depth earthquakes. With varying earthquake scenario, local effects vary in space with frequency. Although the strongest site effect is observed in the transversal component (T), the radial (R) and vertical (V) components are the most sensible to the source mechanism variations of the earthquake scenario (Moldoveanu et al., 1998).

For the complete microzonation of Bucharest, the modeling will be extended to a set of representative cross sections that spans the entire area of the city, and to a set of source parameters typical for the strong Vrancea quakes.

With the modal summation technique, extended to laterally heterogeneous anelastic structural models (Vaccari et al., 1989;

Figure 3 Simplified geotechnical zonation map for the Catania area and the velocities time series calculated, with a cut-off frequency of 10 Hz, at the sites (white triangles) along the thirteen cross-sections shown. The laterally heterogeneous models are built up putting in welded contact (from 2 to 4) different 1-D models: the regional 1-D model is chosen as bedrock model and the geotechnical information related with the selected boreholes are used for the local 1-D models. The site locations are chosen both in the proximity of the boreholes, and at the edges of the section. Each signal is scaled to the maximum value of PGV over the entire area (black triangle) and the time window is 20 s long (from Romanelli et al., 1998).

Romanelli et al., 1996), a database of synthetic signals has been generated, which can be used for the study of the local response in a set of selected sites, located within the Catania area. The ground shaking scenario so far constructed (Romanelli et al., 1998) corresponds to an earthquake of the same size as the destructive event that occurred on January 11, 1693. Making use of the simplified geotechnical map for the Catania area, we produce maps of the expected ground motion over the entire area (see Figure 3), and, using the detailed geological and geotechnical information along a selected cross section, we study the site response in a very realistic case (see Figure 4). The main result, so far, is that, in order to perform an accurate estimate of the site effects, (1) it is necessary to make a parametric study that takes into account the complex combination of the source and propagation parameters, and (2) obtained with simplified structural models have a limited applicability and detailed models should be preferred (Romanelli et al., 1998).

A large quantity of descriptions of earthquakes that have been felt in Rome is available (Molin et al., 1995). The realistic modeling of the seismic input gives a simple and natural explanation of the damage distribution observed as a consequence of 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 well-documented distribution of damage in Rome, caused by the Fucino earthquake, is, in fact, successfully compared by Fäh et al.

(1993) with the results of a series of different numerical simulations, using AMAX and W. Since the correlation is good between AMAX, W and the damage statistics, it is possible to extend the zoning to the entire city of Rome, thus providing a basis for the prediction of the expected damage from future strong events.

The highest values of the spectral amplification are observed at the edges of the sedimentary basin of the Tiber, and strong amplifications are observed in the Tiber's river bed. This is caused by the large amplitudes and long duration of the ground motion due to (1) low impedance of the alluvial sediments, (2) resonance effects, and (3) excitation of local surface waves (Fäh et al. 1993). A preliminary microzoning map has been produced by Vaccari et al. (1995). The microzonation map and the response spectra, corresponding to the three main seismogenic zones around Rome, are shown in Figure 5.

Conclusions

The project represents a contribution to seismic disasters' preparedness. It produces results using what is available now and it improves scenarios as new data become available.

The availability of realistic numerical simulations allows significant progresses in ground motion mapping. This powerful tool enables us to estimate the amplification effects in complex structures exploiting the available geotechnical, lithological, geophysical parameters, topography of the medium, tectonic, historical, paleoseismological data, and seismotectonic models. The ground motion modeling technique applied in this project proves that it is possible to investigate local effects even at large epicentral distances, taking into account both the seismic source and the propagation path effects.

Traditional methods for seismic microzoning can only lead to a kind of "post-event" action whose validity cannot be easily extrapolated in time and to different regions. On the contrary, the computation of realistic seismic input, taking source and propagation effects into account, utilizing the huge amount of geological, geophysical and geotechnical data already available, goes well beyond the conventional deterministic approach and gives a very powerful and economically valid scientific tool for seismic microzonation. Because of its flexibility, the method is suitable for inclusion in new integrated procedures, a kind of compromise between probabilistic and deterministic approaches.

The ability to estimate realistic seismic hazard at very low probability of exceedance may be important in protecting against rare earthquakes, and the deterministic approach, based upon the assumption that several earthquakes can occur within a predefined

Figure 4 Detailed geotechnical cross-section (bottom) and corresponding model for detailed section S10. The distance along the section is measured in km from the source, while the vertical scale is in m. The acceleration time series and the theoretical site responses are shown at six selected sites along the section (from Romanelli et al., 1998).

seismic zone, represents a conservative definition of seismic hazard for pre-event localized planning for disaster mitigation.

Numerical simulations of the seismic source and of the wave path are a more adequate technique than making estimates based on recorded accelerograms (empirical Green functions), since such records are always influenced by the local soil condition of the recording site. With realistic numerical simulations it is possible to obtain, at low cost and exploiting large quantities of already available data, the definition of realistic seismic input for the existing or planned built environment, including special objects. The definition of realistic seismic input can be obtained from 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 built environment, and, therefore, supply a particularly powerful tool for the prevention aspects of Civil Defense.

A general conclusion of the waveform modeling is that the presence of near-surface rigid rocks is not sufficient to classify a

Figure 5 Microzonation map of Rome (top), based on the computation of realistic seismic ground motion due to three seismogenic zones around Rome: the Fucino area, the Alban Hills and the Carseolani Mountains. For the five zones identified in the map, the maximum absolute spectral acceleration (5% damping) is given (bottom).

location as a "hard-rock site", since the existence of underlying sedimentary complex(es) can cause amplifications due to resonance effects. A correct zonation requires therefore knowledge of both the thickness of the surface layer and of the deeper parts of the structure, down to the real bedrock. This is especially important in volcanic areas, where high-rigidity volcanic flows often cover low-rigidity alluvial basins.

The procedure illustrated here, for the mitigation of seismic hazard, is scientifically and economically valid for the immediate (no need to wait for a strong earthquake to occur) seismic microzonation of any urban area, where geotechnical data are available.

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Giuliano F. Panza is professor of seismology in the Department of Earth Sciences at the University of Trieste, and is head of the SAND Group of the ICTP at Trieste. He received his Laurea in physics (1967) from the University of Bologna and performed PostDoc research at the UCLA University. He is fellow of Accademia Nazionale dei Lincei, of Accademia Europae, and of Third World Academy of Sciences. He is leader of several projects funded by EC related to seismic hazard assessment.

Franco Vaccari is a researcher of GNDT (National Group for the Defense against Earthquakes) in the Department of Earth Sciences at the University of Trieste, Italy, where he received Laurea in geology (1986) and Ph.D. (1989) in geophysics. His recent research interests involve seismic hazard assessment, seismic zoning and microzoning, and computational aspects of seismology.

Fabio Romanelli is a researcher of GNDT (National Group for the Defense against Earthquakes) in the Department of Earth Sciences at the University of Trieste, Italy, where he received Laurea in physics (1993) and Ph.D. (1998) in geophysics. His research involves the study of the excitation and the propagation of seismic and tsunami waves in laterally heterogeneous media. The recent focus of his work has been the theoretical estimation of side effects.