Assessing seismic risk at different geographical scales: concepts, tools, and procedures

Istituto di Ricerca sul Rischio Sismico - CNR, Milano, Italy

P. Carrara & D. Musella
Istituto per le Tecnologie Informatiche Multimediali - CNR, Milano, Italy

M. Garcia-Fernandez & M. J. Jimenez
Instituto de Ciencias de la Tierra "Jaume Almera" - CSIC, Barcelona, Spain

Departamento de Ingenieria del Terreno y Cartografica - UPC, Barcelona, Spain

R. Soetters & M. T. J. Terlien
Department of Earth Resources Surveys - ITC, Enschede, The Netherlands

A. Cherubini, P. Angeletti, A. Di Benedetto & M. Caleffi
S.T.E.C. - Ingegneri e Architetti s.r.l., Roma, Italy

J. J. Wagner & P. Rosset
Centre d’Etude des Risques Geologiques, UNIGE, Geneve, Switzerland

Keywords: Seismic risk, vulnerability, systemic damage, GIS, Expert System

ABSTRACT

This paper reports the main results of the EC-Project SERGISAI. This project developed a computer prototype where a methodology for seismic risk assessment has been implemented. Standard codes, Geographic Information Systems and Artificial Intelligence Techniques compose the prototype, that will enable the end user to carry out a proper seismic risk assessment. This prototype is a first attempt to integrate tools, codes, methods for assessing the expected damage and is meant to become a useful support both for civil protection and for land use planning agencies.

1 INTRODUCTION

The SERGISAI project developed a computer prototype where a methodology for seismic risk assessment has been implemented. Experts of various disciplines, including seismologists, engineers, planners, geologists, and computer scientists, cooperated together in an actual multidisciplinary process to develop this tool. Models and codes that have been selected are meant to be used at different steps of the risk assessment procedure. There are reasons for those choices; however, this does not mean that in the future end-users will not be free to change some codes with others they prefer or whenever new and better models become available.

The approach has been designed to be useful to civil protection and land use planning agencies, by adapting the analysis to the following geographical scales: local, sub-regional and regional. Risk factors have been treated in the most suitable way for each one, in terms of level of detail, kind of parameters and units of measure. Identifying various geographical scales is not a mere question of dimension; on the contrary entities to be studied correspond to areas defined by administrative and geographical borders. The prototype was applied in the following areas: Toscana in
Italy, for the regional scale, the Garfagnana area in Toscana, for the sub-regional scale, and part of Barcelona city, Spain, for the local scale.

2 DESCRIPTION OF THE PROTOTYPE

The idea of chain is incorporated in the methodology which was implemented in the prototype, where each step of the seismic analysis is connected to the following so to obtain maps showing where and with which severity losses have to be expected. This “chain mode” of analyzing the disaster is mirrored by the computer prototype, and precisely in its modularity. In fact single codes or models to calculate the various factors leading to the risk assessment are not new in general, apart from some attempts to evaluate systemic vulnerability. What is new is the idea to link all those models together to obtain a comprehensive seismic risk assessment tool that can be used by agencies in charge of earthquake prevention and mitigation.

The prototype is physically made of two main parts: the Expert System (based on Nexpert, from Neuron Data Inc.) and the Geographical Information System (GIS) (based on Arc/Info, from ESRI Inc.) (see Fig. 1). Codes and software written in traditional languages are connected to the GIS: spatial data can be used by those codes for computations, the results of which can be mapped in their turn in the GIS. The latter and the codes have been kept separate for two main reasons: in many cases the translation of existing software into the AML language of Arc/Info is very time-consuming, if not impossible at all. Secondly the resulting computational performance would have diminished dramatically if compared to the “outside feeding” code solution; furthermore the final structure would have been extremely rigid and would not have permitted any change of implemented codes.

The Expert System allows to carry out more complex evaluations regarding those elements for which a rule-based-structure procedure seems preferable. The two main components the GIS and the Expert System are interfaced in a friendly way to enable non-expert users to carry out the most important steps of the seismic risk analysis process.

![Diagram of the prototype](image-url)
3 PROCEDURES AND TOOLS

Seismic risk is defined as the probability of losses directly or indirectly provoked by earthquakes, losses that might be suffered either by the population or by the built up environment as well as by the economic system. At present no consensus has been reached by the “disaster research” community with respect to an acceptable measure of damage, and therefore of risk. Some criticize quantitative approaches providing, for a given seismic input, estimates of damaged buildings, expressed in monetary terms, and estimates of casualties. A balance must be reached however between extremely complex methods, which might end up paralyzing action, and too poor analyses, that sacrifice crucial elements just to obtain quantitative results at all costs. A multicriteria approach, that seems preferable to get such a balance, has been implicitly chosen in this project, where both probabilistic and deterministic methods are used in the evaluation procedure.

3.1 The hazard factor

Probabilistic and deterministic approaches serve to produce either a risk assessment map or a scenario. Codes that were chosen for implementation fulfill the following basic requirement: they adapt to existing recording of ground motions and to the quality of available data.

The probabilistic method for seismic risk assessment which was implemented is based on the assumptions that the seismic hazard at a site is fully described by the inter-occurrence time distribution $F(t)$ and by the local intensity distribution $F_I(i)$ and that the inter-occurrence times $t$ and intensity $I$ are independent and random variables (Grandori et al. 1984).

At the regional level the software prototype produces the maps of intensities (i.e. see figure 3) or acceleration for return periods, using as input data (see Fig. 2) the Italian catalogue of events (Camassi & Stucchi 1996) and the seismic sources model developed by Scandone et al. (1996).

Figure 2. Seismic sources model and the earthquakes with intensity greater then VIII MCS.

Figure 3. Map of intensities for a mean return period of 475 years.

With respect to the production of seismic scenarios some deterministic codes are available in the prototype. To evaluate the seismic scenarios in Barcelona the Empsyn code, based on the Empirical Green's Function (EFG) technique, has been chosen. This technique, developed according to the approach proposed by Hutchings (1991 & 1994), allows to calculate strong ground motion time histories.

The method is well suited for events in the magnitude range 5.0-7.0 and one of its main advantages is that few events are required to simulate a large one. This technique was used at the local scale, in Barcelona, where the attention was focused on the production of scenarios. The lack of acceleration records within Barcelona city and the need for characterizing ground motion in terms of both amplitude and frequencies made it necessary to obtain seismic input scenarios using avail-
able digital short-period seismic recordings obtained in rock-outcrop stations not far from Barcelona. The EGF-technique was applied to simulate moderate events (magnitudes 5.0 to 6.0) which can be reasonably expected to strike the city. Aftershocks recordings of three recent earthquakes which occurred in 1987, 1991, and 1995 have been used to compute seismic input scenarios at the bedrock level.

A further computation should be performed to account for local soil effects. The linear equivalent 1-D method SHAKE91 (Idriss & Sun 1992), which has been implemented in the prototype, has been used for this purpose using the available geotechnical data of Barcelona (Losan 1978). The final result of the deterministic hazard combined with local amplifications analysis is provided in a map of PGA values expected at various sites in Barcelona city. The PGA map is the input layer for the damage index approach in order to assess expected damage to buildings in the part of Barcelona City where vulnerability assessment was carried out.

3.2 Induced hazards: landslides

The second element of the risk chain is given by all potential sources of damage that exist in an area, and which might be triggered by a seismic event. In the prototype landslides have been considered as one of the most frequent events connected with earthquakes. The analysis to evaluate the probability of a landslide to occur under given environmental condition can be static, pseudostatic and dynamic. In this paper the application of the pseudostatic and dynamic method are shown, and the results of two types of analysis performed by the prototype, are discussed. First it was analyzed the entire Garfagnana area, with a lower level of detail and accuracy, and performed on pixel base, that is a regular square terrain unit, then a sub-area, approximately from Piazza al Serchio, to the North, to Pontecosi, to the South, with a higher level of accuracy and detail, performed on slope.

The data collected and digitized were: topography, geology, hydrography, infrastructures, buildings, landslides (1300 mass movements, figure 4), meteorological and geotechnical.

![Figure 4. Available landslides map of Garfagnana area.](image-url)
For the entire Garfagnana area and in the case of pseudostatic analysis the infinite slope method to determine the critical horizontal acceleration coefficient \( (K_c) \), as the minimum acceleration needed to move the mass, was applied. The parameters, necessary to calculate the stability factors, are represented by the geometrical and geotechnical characteristics of the slope and by its hydrological setting. The spatial groundwater distribution has to be obtained by hydrogeological mapping in combination with a statistical analysis of distribution of springs, since the geological setting is too complex and the amount of data too limited to allow for a mathematical modeling approach. In the case of dynamic analysis the landslide displacement during an earthquake has been calculated by a statistical method using as seismic input Peak Ground Acceleration \( (Pga) \) and Arias Intensity \( (Ia) \) maps, using an empirical relationship between the displacement, as function of the critical acceleration \( (K_c) \) and seismic parameters (Luzzi & Pergalani 1994; Ambraseys & Srbulov 1995). This is performed applying the Newmark’s method (Newmark 1965) to different geometric and geotechnical situations using several accelerograms with their characteristic parameters.

The maps of \( Pga \) and \( Ia \) values are evaluated through the analysis of seismic hazard using a relationship between the values of intensity-acceleration and intensity-\( Ia \) developed by Margottini et al. (1992).

For each location it is assumed that the movement can start if a given \( Pga \) exceeds the critical acceleration; then its displacement is calculated, as a function of \( Ia \), according to the empirical relationship mentioned above. Overlaying the displacements and infrastructures maps it is possible to evaluate the influence of displacements on infrastructure, a result which is extremely important to assess systemic vulnerability as it will be discussed in the next paragraph.

Figure 5. Average critical horizontal acceleration coefficient \( (K_c) \) map.
For the sub-area only the pseudostatic analysis has been performed, with a higher level of accuracy and detail, in particular the availability of geotechnical data, allowed the evaluation of statistical parameters for the frictional angle and the cohesion and therefore the calculation of probabilistic distributions. The Montecarlo simulation has been applied to the $K_c$ calculation for each slope segment. After running several times, i.e. 1000, the infinite slope formula, the $K_c$ for each slope has been defined as mean and standard deviation with its probabilistic distribution (Fig. 5).

3.3 The vulnerability factor

Defining vulnerability as a measure of how prone is a system to be damaged in case of earthquake by both seismic and induced hazards, an attempt has been made to move from the assessment of individual buildings, which are usually considered in this type of analysis, to the evaluation of the performance of urban and regional areas. A comprehensive approach to assess systemic vulnerability, especially when this term is referred to urban and regional systems, has still to be fully developed. Parameters to measure urban and regional vulnerability are not so homogeneous as it might be the case for other systems, because many social, economic factors as well as elements related to the built environment must be forcibly taken into account.

Furthermore, both time and spatial dimensions have to be considered: with respect to the first, it is almost impossible to limit the analysis to the instant of the seismic impact, as the response to the earthquake at the emergency and during the reconstruction is equally prominent, especially when preventive measures have to be foreseen. In very general terms it can be argued that at the impact most of the physical damage occurs, provoked by the earthquake or by induced hazards, and affecting physical objects and people, whereas in the emergency both induced damage and systemic damage may hinder search and rescue activities. During reconstruction some physical damage and some systemic damage will not be fixed, or will be fixed in such a way that a part of the stricken area and of its inhabitants will suffer permanent losses (human as well as economical). It is possible to refer to the latter as to damage in the long run, that will persist after the period of time needed for recovery and reconstruction.

Similarly to what was done when buildings vulnerability was studied for the first time, two approaches were proposed to be pursued in the project, in order to develop this field of research also from a theoretical point of view. Those are the vulnerability matrix and the vulnerability index similar to the approach used for the buildings.

The first aims at extracting patterns of potential failures from information of damage and losses suffered in past events. Detailed information regarding the Irpinia and the Central Italy earthquakes (1980 and 1984), as well as the more recent Umbria-Marche earthquake (September 1997) were extensively analyzed. Some factors which are supposed to influence the response of an inhabited settlement as a whole (besides the response of single houses) have been selected and correlated to the cost of repair and reconstruction after those three events, subdivided according to various budget items (so to separate expenditure for building construction material from other types of costs).

Identifying for example the number of access ways and the relationship between the latter and the morphology of urban centres as two of the most important parameters to be considered, is a useful information per se, but it can also help better calibrate qualitative and quantitative functions developed with the vulnerability index method.

The latter in fact tries first to structure the modeling of systemic vulnerability, using existing literature and past earthquake experiences.

3.3.1 Buildings vulnerability

A sub-system which has already been studied by previous research and tested over more than ten years refers to buildings and particularly to residential buildings (Benedetti & Petrini 1984) and is based of the vulnerability index approach.
Table 1. Numerical scale of vulnerability index $V$ (1). The weight of the parameters 5, 7 and 9 varies in a range comprised in 0.131 - 0.261; depending on some elements like: the percentage of rigid well connected diaphragms, the presence of open gallery floors, and the roof weight.

<table>
<thead>
<tr>
<th>I</th>
<th>Parameter</th>
<th>Classes ( $p_i$ )</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>$w_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Resistance system organization</td>
<td></td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>45</td>
<td>0.261</td>
</tr>
<tr>
<td>2</td>
<td>Resistance system quality</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.065</td>
</tr>
<tr>
<td>3</td>
<td>Conventional resistance</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.392</td>
</tr>
<tr>
<td>4</td>
<td>Position of the building and foundations</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.196</td>
</tr>
<tr>
<td>5</td>
<td>Diaphragms</td>
<td></td>
<td>0</td>
<td>5</td>
<td>15</td>
<td>45</td>
<td>var.</td>
</tr>
<tr>
<td>6</td>
<td>Plan configuration</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.131</td>
</tr>
<tr>
<td>7</td>
<td>Elevation configuration</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>var.</td>
</tr>
<tr>
<td>8</td>
<td>Maximum distance between walls</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.065</td>
</tr>
<tr>
<td>9</td>
<td>Roof type</td>
<td></td>
<td>0</td>
<td>15</td>
<td>25</td>
<td>45</td>
<td>var.</td>
</tr>
<tr>
<td>10</td>
<td>Nonstructural elements</td>
<td></td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>45</td>
<td>0.065</td>
</tr>
<tr>
<td>11</td>
<td>Preservation state</td>
<td></td>
<td>0</td>
<td>5</td>
<td>25</td>
<td>45</td>
<td>0.261</td>
</tr>
</tbody>
</table>

Eleven parameters related to components as well as to qualitative features have been identified as crucial to assess how prone is a building to be damaged by ground shaking. Each parameter is given a score, according to four classes ranging from poor to good conditions (D to A), while the overall vulnerability index is given by:

$$V = \sum_i p_i \ w_i$$

where: $p_i$ is the score of the index parameter and $w_i$ is the weight of each parameter.

The final score can range from 0, when present building codes requirements are met to 100, in case of very vulnerable structures (table 1).

At the local scale the vulnerability index (Fig. 6) of the traditional district of Barcelona, called the Eixample was calculated. This area contains more than 7000 buildings, organized in regular blocks of 113 times 113 m, and covers 750 hectares of the city. Most of the buildings in this area have unreinforced masonry structure, and were built between 1860 and 1940. Four parameters of the vulnerability index, namely the conventional resistance, the position of the building and of the foundation, the plant shape and elevation shape were obtained directly from the database provided by the City Council. The maximum distance between walls, has been obtained with sampling techniques. Another set of parameters, regarding the resistance system, resistance system quality and preservation state can be inferred from data (e.g. the age of the buildings) contained in the database of the City Council. Finally, the horizontal floor system, the roof type and the non structural elements have been simulated using again sampling techniques (Barbat et al. 1996).

At the regional level the vulnerability assessment can be carried out adopting a statistical approach that has been developed for this purpose.

In fact the method for evaluating single buildings vulnerability cannot be applied to large areas, not only because it would cost too much in money and time to survey each building, but also because the result would be useless at this scale, where the information needed for decision making is less detailed. Census data are a primary source in this case: they cover homogeneously the whole country though the information they provide permits only to estimate the total number of buildings, the total volume and a poor classification in terms of age and few typological parameter (the material, the age, the level of maintenance, the number of floors and the structural context).

The vulnerability assessment at this scale requires that all the buildings be grouped in few classes that can be obtained using this low quality data (e.g.: masonry, reinforced concrete, age, floors number); vulnerability information collected with surveys in previous research and applications at regional or local levels are reorganized in the same classes defined for census data. Finally the statistical processing of data gives vulnerability distributions for each class of building identified through the census data.
This vulnerability index serves to calculate the risk assessment adopting the damage index approach. Methods to obtain the latter have been already developed and tested in several areas adopting the damage index (expressed by a continuous function form, in the 0-100 range) approach to quantify damage to buildings struck by a seismic event (Angeletti 1984 & 1988).

In order to calculate the latter, the following two factors must be determined: first, a probabilistic model forecasting the future seismic activity, \( f_y(y) \), in the area to be studied; and, second, a model providing an estimate of expected levels of damage as a function, \( d(y,V) \), of the seismic input, \( f(y) \), and of the vulnerability of exposed structures, \( V \).

The expected value of damage provided in annual rate, \( (D_p) \), which is more reasonable for planning purposes particularly at the regional and sub-regional scale has been calculated.

The relation \( d(y, V) \) is obtained from a set of curves that were identified to correlate vulnerability values and actual damage observed in buildings hit by the Friuli and the Central Italy earthquakes (1976 and 1984). This correlation has been reviewed since its first version published in 1989 (Guagenti & Petrini 1989), calibrating data coming from four centres that were extensively surveyed: Vezzone, Tarcento, Barrea, and San Daniele. Those curves, shown in figure 7 (Meroni et al. 1995; Grimaz et al. 1997), represent the expected damage due to a given value of the ground acceleration. Different vulnerability situations move this value from one curve to another, increasing or decreasing it.

As an example, in figures 8 and 9 two maps, produced with SERGISAI software prototype, with different measures of risk are shown.
3.3.2 Another example: the health care sub-system
Another sub-system which has been analyzed in this project concerns the health care system, chosen because it is a crucial component in emergency management and because it is deeply interlaced with several other systems.
First, some parameters describing the vulnerability of any single hospital have been identified, describing the physical vulnerability of the building, of internal machinery and lifelines and the organizational vulnerability, which measures the lack of organizational competence to face mass emergencies. It has been proposed to measure the direct damage provoked by the earthquake to the hospital and particularly to those wards essential to cure injuries which are more frequent in this case (Haas 1977) in number of lost beds.

The second step requires to move to the outside and to evaluate how important is for an entire area the loss of a number of beds in a single hospital; in order to do this, other health facilities in the area and in the periphery of the affected area must be taken into account, as well as their overall organizational vulnerability, due to the lack of coordination among hospitals and with other civil protection agencies. In fact the ability to sort injured people among various hospitals is the result of several previous correct assessments regarding the average number of available beds in any hospital, the state of roads and other access ways which might be interrupted because of collapsing bridges or landslides, and the functionality of hospitals in case external lifelines have been severely disrupted.

As a first attempt, in figure 10, the assessment of the vulnerability of the health care system has been evaluated in the Garfagnana area. Combining different kinds of information and using the GIS function Network analysis it was possible to estimate the time needed for injured to be taken to the closest hospital in Garfagnana. Four facilities were considered: the ambulatory in Piazza al Serchio, in the northern part of the Garfagnana, and the three hospitals in Castelnuovo Garfagnana, in Barga, and in Lucca (the last two outside the area under investigation).

Figure 10. Allocation of the Garfagnana area at different hospitals.

4 THE DECISION MAKING SIDE OF THE PROTOTYPE

The methodology that has been implemented in the prototype, makes it much closer to a decision support tool rather than to a set of independent codes giving certain outputs. It is in fact an oriented approach towards seismic risk assessment, addressing the main elements that should be taken into account to leave open the largest number of alternative mitigation and preventive strategies.
The vulnerability assessment involves not only physical elements, but also systemic links, organizational factors, and it covers, besides the moment of the actual impact of the earthquake, also the emergency and the reconstruction. Then, it is easier to articulate prevention policies according to available budgets and resources. In order to reduce expected losses of the disaster, it is possible to take action regarding various systems improving their performance at different phases. Various alternative options can be weighed one against the other by decision-makers. For example in the case that was illustrated regarding the vulnerability of the health care system, options like consolidating those hospital buildings which are more vulnerable or instead improving access networks to more resistant hospitals can be compared and an agreement can be reached with respect to which is preferable to ease emergency operations, or simply considering available budgets.

Another example is provided by the vulnerability assessment on residential buildings. Further development of the prototype will include a computer code to carry out cost-benefit analysis, allowing end-users to compare the cost of reconstruction or of repair of damaged houses in case of earthquake, with the cost of preventive consolidation. This comparison can be even more detailed, by showing differences among actions taken on various combinations of the eleven parameters forming the vulnerability index.

Last but not least, the ability to make seismic risk analyses correspond to different geographical scales might help administrations and decision makers combine preventive measures with other policies, like for example combine environmental restrictions with seismic codes or taking into account local geological effects when new roads or infrastructures must be designed.

5 CONCLUSIONS

In this paper the results of some applications performed using the prototype have been showed, as for example the probabilistic assessment at the regional scale, while the general framework of the prototype has been sketched in its main features. The project that has been presented in its main features is a first attempt to integrate tools, codes, methods for assessing the expected damage which have been originally developed separately one from the other. Apart from this attempt to put everything in a unique system, which is conceptual before being material (the computer prototype), new areas of investigation or new approaches to traditional areas have been searched. Not everything has been put into the prototype, however the framework that has been developed can be used in the future as a reference to complete the assessment tool.

Other directions for research can be explored starting from what has been done until now. Some of them consists of an improvement of the links among various codes which provide results for seismic and induced hazard analyses, for vulnerability assessment, and for expected damage estimates. Each of those fields could be further developed: however it is felt by the authors that a better interface (which is not a mere technical matter) among them is perhaps more important at the present state-of-the-art than refinements that can be done in anyone of them. Other areas of investigation deserve more attention than they have been granted until now, especially with respect to what has been referred to as systemic vulnerability.

On the ground of the experience gained with this project, it can be suggested that to achieve the last two goals more attention will have to be put on achieving real interaction among scientists of various fields as well as between the scientists’ community and the end-users of their research, that is public administrators and decision makers.

ACKNOWLEDGMENTS

This research was in part supported by the EC Environment Research Programme (contract: ENV4-CT96-0279, Climatology and Natural Hazards).
REFERENCES


