Natural Hazards (2005) 34: 353–374

Preliminary Quantitative Assessment of Earthquake Casualties and Damages

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(Received: 17 October 2003; accepted: 8 September 2004)

Abstract. Prognostic estimations of the expected number of killed or injured people and about the approximate cost associated with the damages caused by earthquakes are made following a suitable methodology of wide-ranging application. For the preliminary assessment of human life losses due to the occurrence of a relatively strong earthquake we use a quantitative model consisting of a correlation between the number of casualties and the earthquake magnitude as a function of population density. The macroseismic intensity field is determined in accordance with an updated anelastic attenuation law, and the number of casualties within areas of different intensity is computed using an application developed in a geographic information system (GIS) environment, taking advantage of the possibilities of such a system for the treatment of space-distributed data. The casualty rate, defined as the number of killed people divided by the number of inhabitants of the affected region, is also computed and we show its variation for some urban concentrations with different population density. For a rough preliminary evaluation of the direct economic cost derived from the damages, equally through a GIS-based tool, we take into account the local social wealth as a function of the gross domestic product of the country. This last step is performed on the basis of the relationship of the macroseismic intensity to the earthquake economic loss in percentage of the wealth. Such an approach to the human casualty and damage levels is carried out for sites near important cities located in a seismically active zone of Spain, thus contributing to an easier taking of decisions in emergency preparedness planning, contemporary earthquake engineering and seismic risk prevention.

Keywords: macroseismic field, population density, human losses, economic cost, prognostic

1. Introduction

Earthquakes become major societal risks when they impinge on vulnerable populations. Many examples illustrate the undesirable consequences of strong earthquakes above all in terms of human life losses, despite the difficulty of setting precise numbers for them. The greatest numbers of killed

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people (N_k) were recorded after the 1556, 1920 and 1976 China earthquakes, magnitude $M = 8.3$ and $N_k = 830{,}000$, $M = 8.5$ and $N_k = 235{,}502$, and $M = 7.8$ and $N_k = 242{,}000$, respectively, according to the Chinese catalog (Institute of Geology and Geophysics, Beijing). The 1923 Japan earthquake, $M = 7.9$, caused a high number of casualties too, $N_k = 142{,}807$. The number of victims may be found in the National Earthquake Information Center (NEIC) catalog and other sources (Ganse and Nerlson, 1981; Utsu, 1990). However, the exact number of casualties is often impossible to establish due to the inherent difficulty of finding and counting them. For the 1908 Messina earthquake, for example, the NEIC catalog gives a number of deaths from earthquake and tsunami between 70,000 and 100,000. For the big 1927 China earthquake the NEIC number of victims is 200,000, but only 80,000 according to the Japanese catalog (Utsu, 1990), and 41,419 according to the Chinese catalog [Institute of Geology and Geophysics (IGG), Beijing]. The magnitude of this earthquake varies from 8.0 (Chinese catalog) to 8.3 (NEIC catalog). The NEIC number of deaths caused by the 1935 Pakistan earthquake is between 30,000 and 60,000. The NEIC number of human victims caused by the 1948 Ashkhabad earthquake is 19,800, although a much greater number (119,000) is also suggested. For the 1976 New Guinea earthquake the NEIC catalog gives 242 casualties, but points out between 5,000 and 9,000 missing people and presumed deaths.

According to the available worldwide data during the twentieth century, almost half a thousand of earthquakes demanded more than 1,615,000 human victims. All these seismic events with focal depth <60 km have been collected in a large database (date, earthquake magnitude, affected region and killed people) by Samardjieva and Badal (2002). The most important and immediate duties to the society in general after a destructive earthquake is rescuing human lives and helping through life-saving operations to all those injured individuals who require medical attendance. In this sense, a prospective evaluation of the possible consequences of a strong seismic event in a seismoactive region is very important for prevention and risk reduction purposes.

Beside human casualties, destructive earthquakes frequently inflict huge economic losses. Thus, an additional problem of very different nature, but also worthy of being considered in a damage and loss analysis, is the direct cost associated with the damages derived from a strong seismic event. Certainly, this is a very different problem related to all man-made facilities (power plants, pipelines, highways and roads, railways, bridges, hospitals, schools, dwelling buildings, lifelines, cultural heritage …) that cannot always be precisely evaluated (file losses, business interruptions), but not of less interest from a merely economic viewpoint. Factors increasing vulnerability include complexity of urban infrastructure, and the technical and social interdependencies of infrastructure systems.

The aim of this paper is to deal with those aspects of seismic risk – casualties and damages – that are directly related to earthquake impact scenarios, and therefore to the preparation of emergency policies and the end-users requirements. We focus our attention on both topics, to their rapid quantitative assessment and to lessen the earthquake disaster in areas affected by relatively strong earthquakes. There is an urgent need to understand the present and future vulnerability of populations and man-made facilities to seismic hazard, and to ascertain the best way to mitigate physical, social and economic impact. Our final goal is the knowledge of potential earthquake losses to improve national programs in emergency management, and consequently to minimize life loss due to earthquakes, and to aid in response and recovery tasks.

2. Methodology

Prognostic estimations of the number of human losses and of the approximate cost associated with the damage in case of earthquake occurrence in selected urban areas are made following a suitable and comprehensible methodology for risk-based loss analysis. The idea is to lessen both the social and economic impact when a seismic event happens in any of those densely populated areas. An outline of the approach is given below.

2.1. ESTIMATING THE EPICENTRAL INTENSITY

For historical events, for which there are no instrumental records, but only information concerning the damage they caused, the intensities are either estimated directly from data, or taken from the catalogues. Instead, for instrumental events, the epicentral intensity can be calculated by inverting its relationship to magnitude and focal depth given for a probed scenario. There are many equations of this type involving seismic intensity near the epicenter, earthquake magnitude and focal depth (Utsu, 1988). For a model earthquake, a regression model proposed by Samardjieva *et al.* (1999) for Iberian earthquakes, which connects magnitude M with epicentral intensity I_0 (≥VI MSK) and focal depth h (≤30 km), was applied and the best linear fit to the data led to the equation:

$$M(I_0, \mathrm{h}) = 0.53\ I_0 + 0.34 \log \mathrm{h} + 0.75 \quad (1)$$

2.2. SELECTING AN ATTENUATION LAW

The distribution of seismic intensity on the Earth's surface shown on isoseismal maps is influenced by major geological and tectonic features, even small irregularities on a local scale, and depends not only on the size of the earthquake and its focal depth, but also on the azimuthal dependence of the source radiation pattern and the attenuation of the ground shake with distance. Regarding the variations of macroseismic intensity or the seismic energy attenuation versus distance, different relationships have been proposed by Gupta and Nuttli (1976), Anderson (1978), Chandra (1979), Chandra *et al.* (1979), VanMarcke and Shi-Sheng (1980), Ambraseys (1985), Tilford *et al.* (1985), Grandori *et al.* (1991), Papazachos *et al.* (1993), and in the course of the last decade by Musson and Winter (1997) among others. Other ground-motion laws may be used, for example those initially proposed by Payo *et al.* (1994) for the Iberian Peninsula and then applied by Samardjieva and Badal (2002) for estimating the expected number of casualties caused by strong earthquakes. López-Casado *et al.* (2000a) have proposed the following ground-motion relations for attenuation of seismic intensity with hypocentral distance in the Iberian Peninsula:

$$I = f(I_0) - a_2 \ln \Delta - a_3 \Delta, \quad f(I_0) = a_{10} + a_{11} I_0 + a_{12} I_0^2 \qquad (2)$$

where a_2 and a_3 represent the terms related to geometric spreading and the rate of absorption, respectively, and $f(I_0)$ is a square function chosen as the best fit to the available data. The hypocentral distance Δ (in km) may be substituted by $(R^2 + R_0{}^2)^{1/2}$, where R is the epicentral distance and R_0 is a value that it is used due to the inherent uncertainty in the focal depth. Equation (2) describes the amplitude of ground motion (felt intensity I) in terms of epicentral intensity (I_0) and distance (Δ) in correspondence with the attenuation tendency. Table I gives the coefficients for several cases from very high to very low attenuation.

2.3. COMPUTATION OF CASUALTIES

Different authors have tackled the estimation of human losses (Ohta *et al.*, 1983; Christoskov and Samardjieva, 1984; Samardjieva and Oike, 1992).

Table I. Coefficients (a_2, a_3) and function $f(I_0)$ in Equation (2) for various tendencies of anelastic seismic attenuation in the Iberian Peninsula (after López-Casado *et al.*, 2000a)

Attenuation	$f(I_0)$	a_2	a_3	R_0	σ	r-sq.
Very high	$3.606 + 0.171 I_0 + 0.078 I_0{}^2$	0.920	0.07615	2	0.49	0.86
High	$6.016 + 0.090 I_0 + 0.069 I_0{}^2$	1.477	0.01035	4	0.46	0.91
Medium	$4.927 + 0.571 I_0 + 0.037 I_0{}^2$	1.445	0.00609	6	039	0.94
Low	$5.557 + 0.902 I_0 + 0.014 I_0{}^2$	1.762	0.00207	2	0.59	0.81
Very low	$7.900 + 0.902 I_0 + 0.014 I_0{}^2$	2.075	0.00201	40	0.46	0.91

R_0, distance in km giving the best fit to the data; R, epicentral distance in km; $\Delta = (R_2 + R_0{}^2)^{1/2}$.
σ = standard deviation in I; r-sq., coefficient of determination.

Shebalin (1985) proposed a classification of earthquake danger by assuming that the expected number of deaths increases with the growth of the population in different nations in the world. Oike (1991) studied the relation between the number of killed or injured individuals and the earthquake magnitude, as well as the temporal variation of earthquake disasters in various countries (Oike and Hori, 1998). Here we follow the method developed by Samardjieva and Badal (2002), from now the SB-method, for estimating the expected number of casualties caused by strong events on the basis of the observed casualties after destructive earthquakes that occurred in the world during the 20th century. The SB-method, demonstrated for Granada (Spain) and Kobe (Japan), is based on a quantitative model that combines earthquake magnitude M, population density D in different parts of the affected territory, and dimensions of the areas with different macroseismic intensity. To compute the number of human losses N_{k} we use regression equations of type

$$\log N_{\mathrm{K}}(D) = \mathrm{a}(D) + \mathrm{b}(D)M \tag{3}$$

where the coefficients a and b are regression parameters depending on the average population density of the affected area and are given in Table II, which contains those correlation coefficients and its respective standard deviation for the most frequent density groups in the world ($D < 25$, $D = 25$–50, $D = 50$–100, $D = 100$–200, and $D > 200$ people/km^2). The expected number of injured people N_{inj} can be computed by means of a relationship suggested by Christoskov and Samardjieva (1984) that leads to the equation:

$$\log(N_{\mathrm{inj}}/N_{\mathrm{k}}) = -0.99 + 0.21M \tag{4}$$

Note that for a fixed magnitude M, N_{inj} is directly proportional to N_{k}. It was assumed that the number of casualties decreases proportionally to the square of the epicentral distance, R, similar to the attenuation of the seismic energy, $N \sim 1/R^2$ (Christoskov *et al.*, 1990). A factor W_I, depending on the radii R_I of the areas of intensity I, was introduced. For instance, in the case of

Table II. Regression coefficients (a, b) in Equation (3) for different population density groups in the world (after Samardjieva and Badal, 2002)

Population density (people / km^2)	a	b	r	σ
$D < 25$	−3.11	0.67	0.84	0.343
$D = 25$–50	−3.32	0.75	0.85	0.342
$D = 50$–100	−3.13	0.84	0.82	0.345
$D = 100$–200	−3.22	0.92	0.70	0.397
$D > 200$	−3.15	0.97	0.75	0.348

r = correlation coefficient for the linkage of the variables.
σ = standard deviation.

observed intensities $I = \text{VII, VIII, IX}$ (MSK), the weighting coefficients W_I are:

$$W_I = 1/[R_I^2 \Sigma_j (1/R_j^2)], \quad j = \text{VII, VIII, IX} \tag{5}$$

Then the number of killed people within the area of intensity I can be determined by the equation

$$N_\text{k}^{(I)} = W_I \cdot N_\text{k}(D_I) \tag{6}$$

where the value of N_k (D_I) is estimated from Equation (3) for the actual average population density D_I in the area of intensity I. Finally, the total number of human losses is a sum of the values $N_\text{k}{}^{(I)}$.

2.4. CASUALTY RATE

The casualty rate, which is defined as the ratio between the number of killed people and the number of inhabitants of the affected region (up to MSK intensity degree VII), is also computed and we shall show its variation for some urban concentrations with different population density later.

2.5. APPROACH TO THE SOCIAL WEALTH

In this item and in the next one we refer to a simple and approximate method of quickly evaluating the economic cost induced by the damages caused by the model earthquake. For this purpose we follow here the work made by Chen *et al.* (1997) based on a macroscopic index of the social wealth calculated from the gross domestic product (GDP) for the region or country subject to seismic risk. Many factors impinge upon the cost, of course; but the method rests upon the assumption of proportionality between man-made facilities and the social wealth of the site estimated through the GDP. It is well known that the GDP measures the total output of goods and services from all resident units (enterprises and self-employed individuals) of a country or region during a fixed time period, usually 1 year. The fluctuation of the GDP has become the most usual measurement of the evolution of the economic activity of a country, and therefore of its growth. Since facilities and population density are closely related, a step in our approach consists in referring the GDP to the inhabitants of the investigated region from the knowledge of the population density distribution all over the partitioned territory. The study area is divided into cells for calculations in a GIS environment. The GDP associated to each cell, namely GDP_cell, is given by the expression

$$\text{GDP}_\text{cell} = (\text{cell population/regional population}) \times \text{GDP}_\text{regional} \tag{7}$$

We still need to correlate the GDP_{cell} with the local social wealth, and we assume it is approximately equal to the GDP_{cell} divided by the fraction that represents the public investment versus GDP:

$$\text{local social wealth} = GDP_{cell} \times [\%\text{investment}/100]^{-1} \quad (8)$$

The public investment is a relatively stable economic variable and a well-known fact for most of the countries (World Bank, 2003). For example, it is of the order of 20–22% for high-income economies and countries belonging to the Organization for the Economic Cooperation and Development (OECD), though it increases up to approximately 33% for China, India, or Japan.

2.6. DAMAGE FUNCTION AND ECONOMIC COST

The last step to complete the quantitative assessment is performed on the basis of the relationship of the macroseismic intensity – MM scale – to the earthquake economic loss in percentage of the wealth. Failing a much better defined damage function $f(I)$, we took into account one supplied by the Munich Reinsurance Group (2000), actually a damage band that expresses the inherent uncertainty in the expected cost due to the different behavior of buildings and structures. The percentage of economic cost as a function of the degree of felt intensity ($> V$) is constrained by two curves closely fitted by the expression

$$\log f(I) = k_0 + k_1 I + k_2 I^2 + k_3 I^3 \quad (9)$$

whose coefficients for maximum or minimum estimates are respectively

$$k_0 = -10.28677, \quad k_1 = 2.83516, \quad k_2 = -0.24213, \quad k_3 = 0.00793$$
$$k_0 = -11.29522, \quad k_1 = 2.72825, \quad k_2 = -0.20344, \quad k_3 = 0.00581$$

Figure 1 shows the upper and lower curves that constrain the damage function. On the basis of the social wealth and the damage function, the earthquake economic loss can be calculated through the formula

$$\text{cost} = \sum f(I) \times GDP_{cell} \times [\%\text{investment}/100]^{-1} \quad (10)$$

where the sum extends to all the cells which integrate the investigated area. Figure 2 shows a flow chart of the working scheme used to compute casualties and damages.

3. Implementation in a GIS Environment

We have implemented the methodology described above using geographic information system software, developing an interactive program to quickly compute earthquake casualties and damages. This program allows the user to interactively change, for example, the input data for the model earthquake

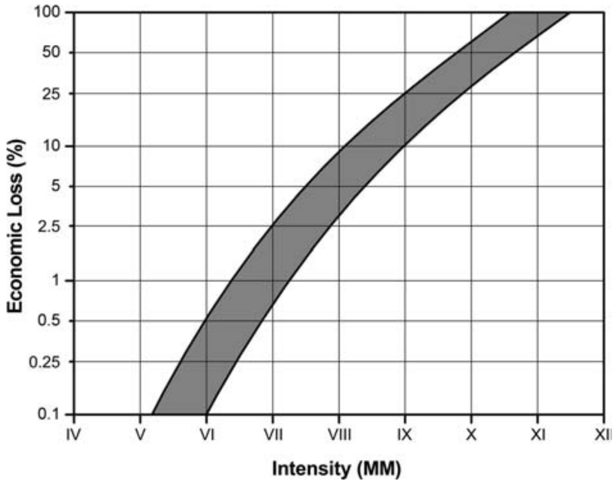

Figure 1. Upper and lower limits (continuous lines) of the damage function (shaded band) defined as the relationship between macroseismic intensity – MM scale – and earthquake economic loss in percentage of the wealth (based on information kindly provided by the Munich Reinsurance Group, 2000).

(location, magnitude, depth) or the seismic attenuation law affecting the shape of the macroseismic field, thus permitting to efficiently show the information on screen. In this way, the user can get an insight into the outputs. The application is designed to foresee the consequences of a hypothesized seismic event of given magnitude or epicentral intensity and coordinates, according to a seismic energy attenuation pattern. It is also possible to work starting from a digitized isoseismal map to reconstruct the scenario of a historical earthquake.

For the purpose of starting the computation from magnitude and focal depth of the model earthquake, we invert Equation (1) to calculate epicentral intensity that we take as initial (maximum) intensity for further calculations. Knowledge of macroseismic intensity, population density and social wealth is necessary to achieve our objectives. The computation of the number of casualties within areas of different macroseismic intensity requires seismic intensity attenuation laws and the handling of a broad-scale geo-referenced database (isoseismals, population densities), which can be satisfactorily made in a GIS environment. We consider for implementation the attenuation law (2). For estimating the expected numbers of human losses and injured people, we follow the SB-method, Equations (3) and (4), and apply the weighting given by Equations (5) and (6).

We have used updated-to-1995 population density data around the epicenter of the hypothesized strong seismic event, in all cases within the affected

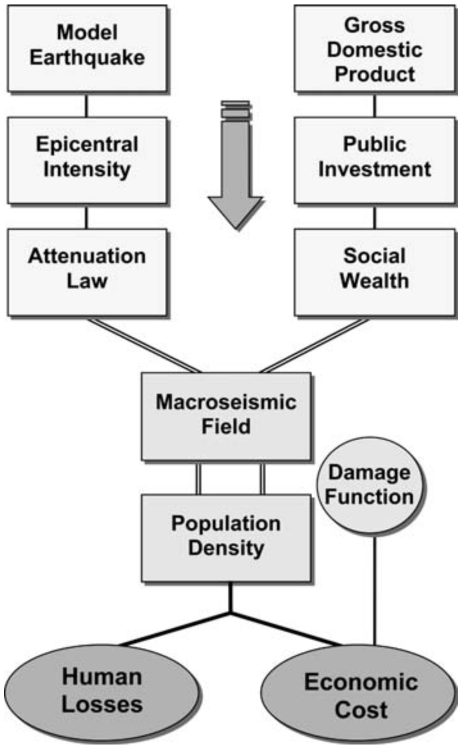

Figure 2. Flow-chart illustrating the working scheme used to compute casualties and damages.

macroseismic area depicted by a seismic intensity attenuation pattern. The gridded population and territorial data, referred to cells of size $2.5' \times 2.5'$ (approximately 4600×3500 m in the study region), were taken from the Center for International Earth Science Information Network (2000). We used the version of this database that takes into account the United Nations' predictions on population growth. A cell was considered inside the zone contoured by an isoseismal line if the geographic center of the cell was inside the zone. The digitized information on boundaries and coastlines used for drawing the maps was taken from the Penn State University Libraries' Digital Chart of the World Server (1992). All indispensable data are of public domain and are easily accessible.

Finally, updated socio-economic information concerning the study area has to be introduced in the database in order to complete the approach (Figure 2). In this sense, beside the damage function, we need data related to the social wealth of the site, and therefore the GDP and the public investment as well. In our case, for Spain, we took these data (updated to 1995) from the

Instituto Nacional de Estadística (2003) and the World Bank (2003): 437,787.73 millions of euros and 21.44%, respectively. To constrain the economic cost depending on the degree of felt intensity we have used an approach based on Equations (7)–(10).

3.1. UNCERTAINTIES

It is easy to understand that the estimates fall into error intervals because of various and very different factors. Unpredictable consequences or undesirable hazard induced by fires, floods, gas poisoning, toxic emissions, harmful radiation, infectious diseases, etc., may appear. In any case it is to be noted that the peculiarities of each zone (seismo-geological factors, soil classes, type and quality of the buildings, antiseismic standards, energy lines, lifestyle, etc.) influence the size of the earthquake consequences. A more realistic evaluation of the prognostic elements would be obtained taking into account all these factors, but it is extremely difficult because of the number of constraints to be adhered to. Moreover, the proposed methodology does enclose a level of uncertainty implied in the predictive Equations ((1)–(4)). The standard deviations for seismic energy attenuation (Table I) and the error bounds to casualties (Table II) are not small, as expected, due to the large variety and dispersion of the original data. In addition, the damage function has also a high level of uncertainty and its fluctuation band results in a large variation of the economic cost. For example, the economic loss ranges between 30 and 60% of the wealth for intensity *X* at MM scale (Munich Reinsurance Group, 2000). Still more, MSK scale is used in this work, but the damage function is referred to MM scale. Since the two scales are practically equivalent (Udías, 1999), any incidence due to conceptual differences between them ought not to be reason for error. However, we develop our application by considering the curves that constrain the economic loss in percentage above and below (Figure 1), and taking its mean value.

3.2. REPEATED COMPUTATION, AVERAGE ESTIMATE AND STANDARD DEVIATION

The results are strongly dependent on the population density in the areas contoured by different isoseismals (Samardjieva and Badal, 2002). The use of precise and updated population density values would lead to more accurate prognostic estimates, as well as the use of gridded data referred to a smaller territorial partition. On the other hand, the prediction is always influenced by the earthquake location. Mislocations of nuclear explosions provide an estimate for the uncertainty in epicentral locations of about 20 km. For all these reasons, in an attempt to supply a more elaborated estimate for both casualties and economic cost, we consider two circles of radii 10 and 20 km around the epicenter of the model earthquake, and repeat the computation moving successively the theoretical epicenter to eight different locations on each of these circles covering all azimuths (at step of 45 °). Thus, for any simulation, we really do not have a single epicenter, but 17 epicenters spaced 10–40 km from each other. In this way, after averaging all the contributions, in practice 17 within a radius of 20 km in each case, we expect to obtain a smoothed value associated to the initial earthquake location. The standard deviation for this value comes from this repeated computation process. Consequently, the prognostics obtained by our methodology should be considered as average estimates and interpreted as the most probable results, unless earthquake resistant designs, building codes, housing standards and other factors are significantly upgraded.

4. Earthquake Impact Scenario and Prognostic Estimations

4.1. THE SCENARIO

Even though the Iberian Peninsula is a region with a moderate seismic hazard, we have carried out an application for a hypothetical seismic event occurring in some Spanish cities. According to the Global Seismic Hazard Map (Shedlock *et al.*, 2000) showing peak ground acceleration (pga) with a 10% chance of exceedance in 50 years, the seismic hazard of the Iberian Peninsula is between low and moderate: 0.04–0.16 g-units. The recently elaborated European-Mediterranean Seismic Hazard Map (Giardini *et al.*, 2002), also calculated for pga with a 10% probability of exceedance in 50 years (475-year return period), supports this same statement. Actually, higher pga-values (approximately 0.24 g-units) can only be observed along the south–southeast segment of the Mediterranean coast of the peninsula. The seismic activity in Iberia is moderate. Figure 3 shows the epicenters of the earthquakes that occurred in the Iberian Peninsula and adjacent areas during the period 1980–2001. As can be seen, most of the epicenters concentrate to the south and southeast of Spain and in the Pyrenees. Almost all earthquakes are shallow events of small magnitude M_S, as their focal depths and magnitudes are mainly ≤33 km and 5.9, respectively.

Badal *et al.* (2000), studying magnitude and spectral analysis, gathered data of only 18 early (1923–1961) instrumental Iberian earthquakes, with focal depths from 6 to 30 km, felt in the peninsula with epicentral intensity equal to or larger than VI MSK. Among these events is the last one that caused important damage and fatalities in Spain: the 19 April 1956 Albolote (southern Spain) earthquake, m_b 5.0, M_S 5.4, approximate depth 8 km, epicentral intensity VII-VIII MSK, 7 victims (plus 4 due to the landslide). Actually, only two events have epicentral intensity VI; the rest

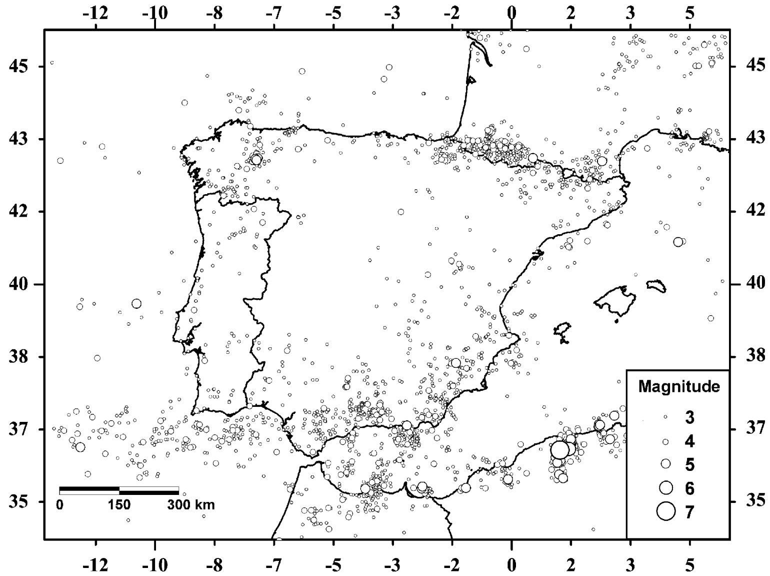

Figure 3. Seismicity of the Iberian region: period 1980–2001, earthquake magnitude $M_S \geq 3.0$. Circles show earthquake epicenters and their size represents magnitude (data taken from the Advanced National Seismic System, 2003).

have intensities VII or VIII MSK. Going back in time, we have data of only two really destructive Iberian earthquakes in the 19th century. The first one is the 21 March 1829 Torrevieja (southeast of Spain) earthquake, m_b 6.3 ± 0.4, M_S 6.9 ± 0.6, approximate depth 10 km (López-Casado *et al.*, 2000b). This big shock, with maximum intensity X MSK (Muñoz and Udías, 1987), produced widespread damage and caused about 1,000 deaths and 1,500 injured individuals (Rodríguez de la Torre, 1984). The second one is the 25 December 1884 Andalucia (south Spain) earthquake, with epicenter between Málaga and Granada, m_b 6.1 ± 0.4, M_S 6.5 ± 0.6, depth 10–20 km (López-Casado *et al.*, 2000b). This shock, which probably had maximum intensity IX MSK (Muñoz and Udías, 1987), completely destroyed several small villages and caused 749 deaths (Udías, 1999). Although there is a significant risk of occurrence of a big earthquake in the future in southern Spain, the truth is that the epicentral area of this shock has not suffered a similar event since. Macroseismic intensities VIII and IX MSK for a return period of 100 and 500 years, respectively, are expected in the area (Payo *et al.*, 1994). Looking at the official seismic hazard map for Spain (500-year return period) provided by the Instituto Geográfico Nacional (IGN), Madrid, one can observe above all that macroseismic intensity up to IX MSK may be expected in the south-southeastern seismically active zone of Spain (Granada area).

4.2. SELECTED SITES

We have adopted an interested viewpoint with respect to the placing of epicenters supposing them in the cities or very close to them. As we want to understand the vulnerability of populations and man-made facilities to seismic hazard, we must consider the higher population levels and most of the man-made facilities, which are obviously near important cities. Considering the concentration of epicenters in the Iberian region (Figure 3), the social and economic interest of possible test sites, and the fact that updated information about intensity attenuation with hypocentral distance in the Iberian Peninsula is available, we have chosen some important cities located either in the south–southeastern seismically active zone or to eastern part of Spain. Figure 4 shows this wide area, the name and location of those cities, and other information of interest, such as the respective number of inhabitants that would be affected by relatively high seismic intensities. In principle, the seismological and socio-economic considerations ought to prevail over other criteria. However, we too consider seismotectonic constraints implicitly, as

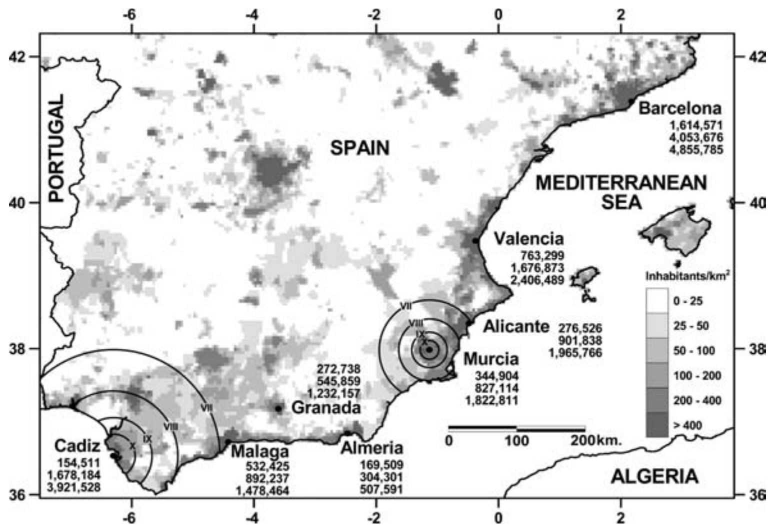

Figure 4. Population density map plotted on a wide part of Spain. The population density is illustrated by quadrangles of 2.5′ × 2.5′, and the observed maximum values correspond to the main urban nuclei. For each city three numbers are given: population (updated-to-1995 data) of the urban nucleus, and populations that would be affected by an earthquake of magnitude 6.0 (degrees VII-IX MSK) or 6.5 (degrees VII-X MSK). Black points mark the initial epicentral locations for simulation. Around two Spanish cities, one located in a low-attenuation medium (Cadiz) and other in a high-attenuation ground (Murcia), the expected circular isoseismals for intensity degrees X to VII MSK for a hypothetical seismic event of magnitude M_S 6.5 and focal depth 10 km, can be seen.

most of the selected test sites are located in faulting zones. Among the selected cities, Barcelona and Valencia, located in the eastern peninsular coast, rank as the nation's second and third biggest cities, respectively, and for that reason only were included in our selection.

4.3. EPICENTERS INLAND

Whenever epicenters are offshore, only the part of the macroseismic field inland provokes human losses. The partial estimates would result to be comparatively smaller than for events with the epicenters inland, and therefore the final average estimate would be smaller too. In order to eliminate any bias in the final results on account of this, we took into account only epicenters inland. Then, by considering the proportionality of inland and offshore areas with respect to the whole area of strong seismic event, the theoretical number of casualties has been recalculated assuming that the number of victims ought to decrease proportionally when the earthquake impact scenario is partially offshore.

4.4. PROGNOSTIC ESTIMATIONS

For the purpose of prognostic let us suppose the occurrence of an Iberian earthquake of magnitude $6.0 \leq M_S \leq 6.5$. In such a case and inverting Equation (1) for the most frequent NEIC focal depth, 10 km, we can expect either an epicentral intensity degree X MSK (M_S 6.5) or IX MSK (M_S 6.0). Assuming those extreme magnitudes and a depth of 10 km, we start the computation with maximum intensity values of 10.2 for M_S 6.5 and 9.2 for M_S 6.0. Except for Cadiz, where the seismic attenuation is low, for the rest of cities the attenuation tendency is high (López-Casado *et al.*, 2000a). According to these attenuation patterns with hypocentral distance (Table I), Figure 4 displays, for magnitude M_S 6.5 and focal depth 10 km, the expected isoseismals around two probed sites, plotted on a population density map.

The outcomes – deaths, injured people, casualty rate and economic loss – for every Spanish populated area considered here are shown in Figure 5. Taking only results as mentioned before, averaging all the quantities computed from different epicenters within a radius of 20 km around the tested urban concentration, the corresponding values and standard deviations for the represented variables are listed in Tables III and IV. The first of them contains the results for a model earthquake of magnitude M_S 6.0, depth 10 km and assuming intensities IX to VII MSK, whereas the second does it for magnitude 6.5, depth 10 km and intensities X to VII MSK. All test areas suffer a disaster in terms of killed and injured people below 400 and 750, respectively, and below 1,150 and 2,700 (round numbers) if the magnitude of the model earthquake is 6.5. From north to south, Barcelona, Valencia,

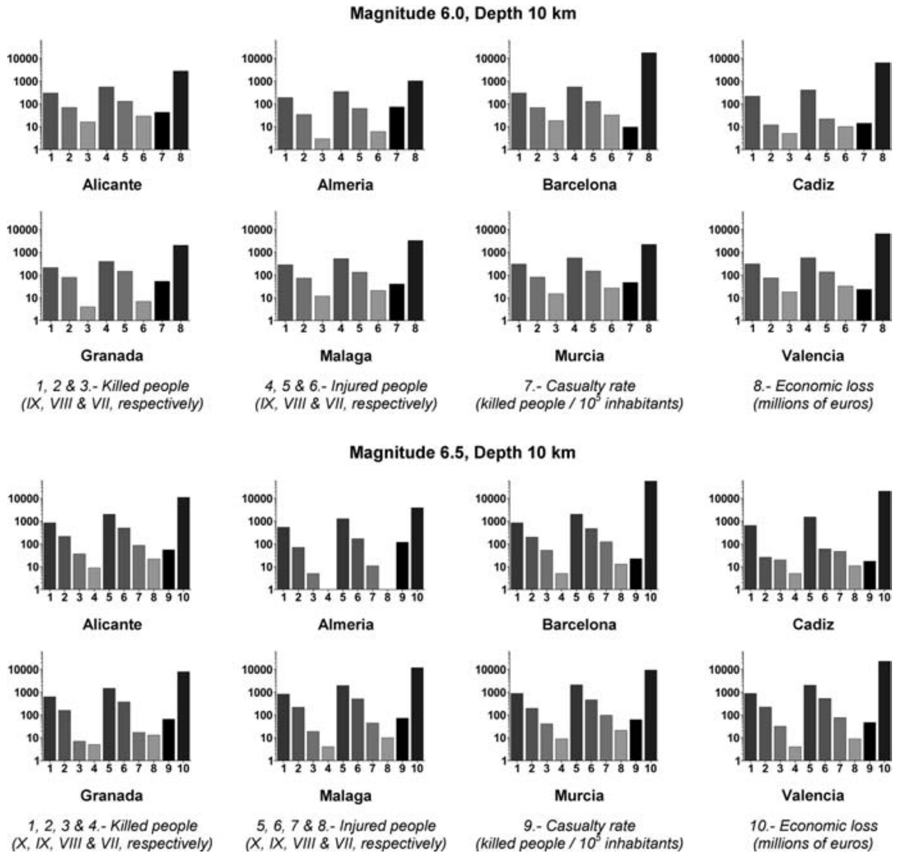

Figure 5. Expected numbers of deaths and injured people, casualty rate and economic loss regarding some urban concentrations in Spain. These averaged data are first computed for a model earthquake of magnitude M_S 6.0 giving intensities in the range from IX to VII MSK, and then for a model earthquake of magnitude M_S 6.5 giving intensities X to VII MSK, in both cases for a hypocentral depth of 10 km.

Alicante, Murcia and Malaga are the cities with more killed and injured people. As the standard deviations are all small, we can say the final results obtained by repeated computation are practically independent on the nearby epicentral location of the model earthquake for any urban concentration. The standard deviations are also comparatively similar for all cases (intensities and cities). Nevertheless, any displacement of the epicenter changes the position of the isoseismals plotted on a population density map, and then a new shape of the macroseismic field may result in unequal partial contributions when the population density fluctuates significantly from a site to other.

The results, which logically depend on the earthquake size, give larger averaged values for magnitude 6.5 than for magnitude 6.0. However, the

Table III. Partial and total values and standard deviations for the variables considered in this study and every tested site, assuming decreasing intensities IX to VII

Area on trial	Killed people				Injured people				Casualty rate[a]	Mean economic cost[b]
	IX	VIII	VII	Total	IX	VIII	VII	Total		
Alicante	302 ± 19	70 ± 5	16 ± 1	**388** ± 24	562 ± 35	131 ± 10	29 ± 3	**722** ± 44	**43.02** ± 2.02	**2812.91** ± 244.93
Almeria	189 ± 32	34 ± 4	3 ± 0	**226** ± 32	352 ± 59	63 ± 7	6 ± 1	**421** ± 60	**74.27** ± 10.94	**1039.07** ± 76.68
Barcelona	303 ± 15	69 ± 5	18 ± 1	**390** ± 21	564 ± 29	128 ± 10	33 ± 2	**725** ± 39	**9.62** ± 0.44	**17471.39** ± 1769.37
Cadiz	220 ± 14	12 ± 1	5 ± 1	**237** ± 14	409 ± 26	22 ± 3	10 ± 2	**441** ± 27	**14.12** ± 0.88	**65582.71** ± 222.80
Granada	212 ± 36	80 ± 6	4 ± 1	**296** ± 34	394 ± 68	148 ± 12	7 ± 2	**549** ± 64	**54.04** ± 6.45	**2026.21** ± 198.70
Malaga	280 ± 20	73 ± 4	12 ± 1	**365** ± 23	521 ± 38	135 ± 8	21 ± 2	**677** ± 42	**40.80** ± 2.48	**3293.71** ± 235.82
Murcia	298 ± 21	81 ± 6	15 ± 1	**394** ± 25	555 ± 39	150 ± 11	27 ± 2	**732** ± 47	**47.51** ± 2.49	**2213.70** ± 101.70
Valencia	305 ± 17	75 ± 4	18 ± 2	**398** ± 32	568 ± 32	139 ± 8	33 ± 3	**740** ± 40	**23.68** ± 1.31	**6520.24** ± 632.43

Model earthquake of magnitude 6.0 and depth 10 km.
[a]Deaths/10^5 inhabitants.
[b]Millions of euros.

Table IV. Partial and total values and standard deviations for the variables considered in this study and every tested site, assuming decreasing intensities X to VII.

Area on trial	Killed people					Injured people					Casualty rate[a]	Mean economic cost[b]
	X	IX	VIII	VII	Total	X	IX	VIII	VII	Total		
Alicante	842 ± 63	212 ± 13	37 ± 4	9 ± 0	**1100** ± 72	1997 ± 150	503 ± 31	87 ± 10	22 ± 1	**2609** ± 170	**55.96** ± 3.30	**11047.06** ± 634.23
Almeria	535 ± 86	71 ± 9	5 ± 1	0 ± 0	**611** ± 81	1268 ± 203	168 ± 22	11 ± 3	1 ± 0	**1448** ± 192	**120.37** ± 16.99	**3863.25** ± 185.04
Barcelona	845 ± 52	197 ± 14	53 ± 4	5 ± 1	**1100** ± 65	2005 ± 123	466 ± 33	125 ± 9	13 ± 2	**2609** ± 155	**22.65** ± 1.28	**58083.93** ± 4094.26
Cadiz	639 ± 39	26 ± 1	20 ± 2	5 ± 1	**690** ± 41	1516 ± 93	613 ± 2	47 ± 5	11 ± 2	**1635** ± 96	**17.60** ± 0.76	**20921.91** ± 617.36
Granada	633 ± 100	160 ± 31	7 ± 1	5 ± 1	**805** ± 70	1500 ± 238	379 ± 73	17 ± 3	13 ± 2	**1909** ± 166	**65.33** ± 6.00	**7869.75** ± 512.43
Malaga	834 ± 53	218 ± 12	19 ± 2	4 ± 1	**1075** ± 64	1978 ± 126	516 ± 28	44 ± 6	10 ± 1	**2548** ± 152	**72.64** ± 3.79	**11865.93** ± 559.71
Murcia	899 ± 57	196 ± 21	41 ± 3	9 ± 1	**1145** ± 70	2132 ± 136	466 ± 50	97 ± 8	21 ± 2	**2716** ± 165	**62.82** ± 3.89	**9357.40** ± 300.45
Valencia	870 ± 50	224 ± 12	32 ± 3	4 ± 0	**1130** ± 60	2062 ± 117	530 ± 28	76 ± 8	9 ± 0	**2677** ± 142	**46.91** ± 2.57	**22763.61** ± 1573.26

Model earthquake of magnitude 6.5 and depth 10 km.
[a]Deaths/10^5 inhabitants.
[b]Millions of euros.

results also depend on the total number of affected inhabitants living together in some area, and therefore on the population density in the zones contoured by isoseismals (Figure 4), which breaks any expectancy of direct proportionality based only upon the people concentrated in an urban nucleus. All the tested sites have less than half a million of inhabitants, except the cities of Valencia and Malaga which overcome this amount, and Barcelona City that has the highest number of inhabitants: 1,614,571 (year 1995). Barcelona anyhow exhibits low results. We think this is due to the computation method with Equation (3) without distinction of population densities >200 people/km^2. Unfortunately we do not have a regression equation for these cases and consequently we cannot obtain more accurate results when operating with population densities exceeding largely that limit.

The casualty rate is rather variable, in any case depending on the total number of affected inhabitants. Again Barcelona exhibits a low casualty rate as a direct consequence of the low number of fatalities in spite of its relatively high population density. Cadiz also shows a low casualty rate in the prognostic, but in this case the result comes from the combination of a low number of victims with a large vulnerable population. This last is the consequence of a low seismic attenuation regime and a wide macroseismic field for the test site (Figure 4). At the other end, Almeria shows the highest casualty rate as a result of the application of Equation (3) with population density >200 people/km^2, when the city has only 169,509 inhabitants (year 1995), and the smaller vulnerable population.

The economic losses also take different values, although some cases need comment. Barcelona has the largest loss, such as corresponds to one of the most developed and rich zones of Spain. Valencia has also a large economic loss on account of the same. However, Cadiz, which is a city with a relatively low number of inhabitants, only 154,511 (year 1995), equally presents an enhanced economic loss due to the low seismic attenuation pattern, which enlarges the territory embraced by the isoseismals (Figure 4) and so increases the extension of the area affected by the seismic impact and therefore the economic cost.

The calculated economic losses involved in our simulation are relatively high, but comparatively feasible. The costliest theoretical earthquake, about 58,000 millions of euros (Table IV), is that of M_S 6.5 located at Barcelona, the most populous city considered. Note that our economic loss estimations refer to the year 1995. In comparison, the economic loss caused by the 1995, M_S 6.9 Kobe (Japan) earthquake exceeded 100,000 millions of US dollars. Another example is the 1994, M_S 6.7 Northridge (California) earthquake, who cost was about 44,000 millions of US dollars (Munich Reinsurance Group, 1999).

Figure 6 allows us to see the results clearly when compared by concepts (killed people, injured individuals, casualty rate, economic loss) for all the

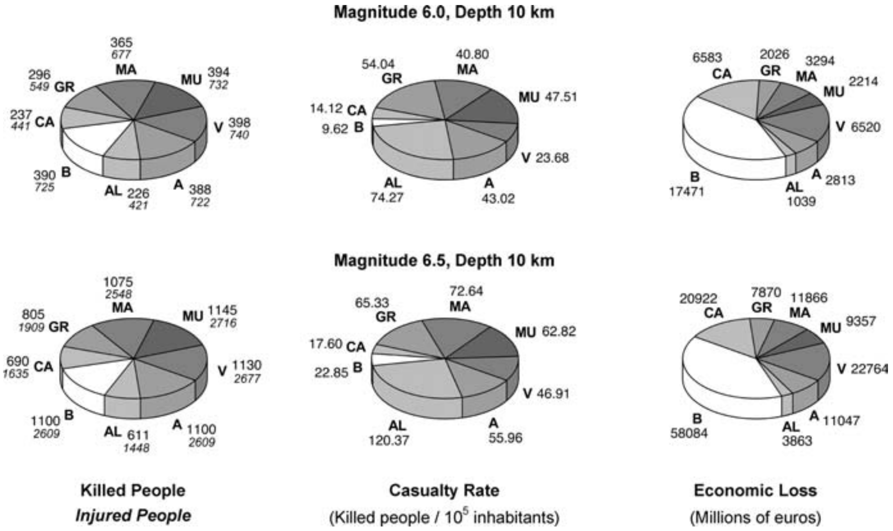

Figure 6. Killed people, injured individuals (in italics), casualty rate and economic loss for some Spanish cities with different population density. These comparisons based on averaged estimations are displayed for two model earthquakes of magnitude M_S 6.0 and 6.5, and focal depth of 10 km. Key to symbols: A, Alicante; AL, Almeria; B, Barcelona; CA, Cadiz; GR, Granada; MA, Malaga; MU, Murcia; V, Valencia.

tested earthquake locations. As the N_{inj}, for a given magnitude, is directly proportional to N_k through Equation (4), a same graphic representation is valid for both variables and so we give the respective estimates together. Obviously, with the exceptions mentioned above, the results support a quantitative jump for the most densely populated and developed places around the biggest cities. Nevertheless, the key for some exceptions is that any problem involving a high population density is solved considering a single density group. Any attempt to obtain a better relationship between killed or injured individuals and the growth of the population and high levels of development, needs additional work focused on a suitable semi-log regression for more detailed population densities.

5. Conclusions

The implemented methodology stresses the population-hazard interaction and is addressed to evaluate the number of human victims and the direct economic cost caused by a seismic disaster *before* it happens. The idea is to quantify the seismic risk through an effective and comprehensible methodology of quickly estimating earthquake casualties and damages. We apply the SB-method based on least-square regression between earthquake magnitude and number of casualties for the most frequent population density groups, in order to compute the expected numbers of dead and injured individuals. In addition, we use an approach based on the GDP and the social wealth to obtain a rough estimate of the economic loss. These amounts obtained from the knowledge of the seismic energy attenuation and the population density distribution, give us an idea of the size of the seismic disaster from a double viewpoint: human and economic. Undoubtedly, this risk information is extremely useful to start and coordinate emergency plans, such as rescue and relief tasks, medical and social attendance, but also activities guided to the economic recuperation of the affected territory, without leaving behind the interest of the insurance companies. The use of modeling systems allows risk managers to find the balance between too little and too much insurance. Combining seismological and socio-economic data sets can greatly improve our understanding of exposure on a wide range of scales.

More specific damages concerning destroyed buildings and other structures are not considered in this work because at present their vulnerability is not well known. The diversity in housing quality and density create large challenges in planning for natural hazard mitigation. In this situation, with poor knowledge of the different vulnerability classes, we have to make use of the damage function defined as the relationship of the macroseismic intensity to the loss ratio in percentage of the wealth. Of course, to supply more precise estimates would require the use of a better-defined damage function, for example adjusted to the available data for the study zone. Damage functions based on fragility curves, giving probabilities of exceeding damage states for a given level of ground motion, would be an alternative way. Regionalized or local data of the GDP instead of population-weighted GDP data for the whole national territory would lead to more accurate results, too.

Finally, the working scheme developed here in a geographic information system environment may be easily extended to other study cases by considering the pertinent seismic and economic information provided by previous research work and public national or worldwide sources.

Acknowledgements

We are indebted to all those individuals who contributed to the production of the data sets used in this article. We thank the institutions and companies (Center for International Earth Science Information Network, Instituto Nacional de Estadística, World Bank, Penn State University and Munich Reinsurance Group) that supplied us information for this study. Helpful comments and suggestions from anonymous reviewers are gratefully acknowledged. The authors MV and AG received funding from the Diputación General de Aragón, Spain, and the European Social Fund, PhD grant B037/2001, and from the Spanish Ministry of Education, PhD grant AP2002-1347, respectively.

References

Advanced National Seismic System (ANSS): 2003, *Composite Earthquake Catalog* (http://quake.geo.berkeley.edu/cnss/).

Ambraseys, N.: 1985, Intensity-attenuation and magnitude-intensity relationships for Northern European earthquakes, *Earthq. Eng. Struct. Dyn* . **13**, 733–778.

Anderson, J. G.: 1978, On the attenuation of Modified Mercalli intensity with distance in the United States, *Bull. Seism. Soc. Am.* **68**, 1147–1179.

Badal, J., Samardjieva, E., and Payo, G.: 2000, Moment magnitudes for early (1923– 1961) instrumental Iberian earthquakes, *Bull. Seism. Soc. Am.* **90**, 1161–1173.

Center for International Earth Science Information Network (CIESIN); International Food Policy Research Institute (IFPRI); and World Resources Institute (WRI): 2000, *Gridded Population of the World (GPW)*, Version 2, CIESIN, Columbia University, Palisades, New York (http://sedac.ciesin.columbia.edu/plue/gpw).

Chandra, U.: 1979, Attenuation of intensity in the United States, *Bull. Seism. Soc. Am.* **69**, 2003–2024.

Chandra, U., McWhorter, J. G., and Nowroozi, A.: 1979, Attenuation of intensities in Iran, *Bull. Seism. Soc. Am.* **69**, 237–250.

Chen, Q. F., Chen, Y., Liu, J., and Chen, L.: 1997, Quick and approximate estimation of earthquake loss based on macroscopic index of exposure and population distribution, *Nat. Hazards* **15**, 217–229.

Christoskov, L. and Samardjieva, E.: 1984, An approach for estimation of the possible number of casualties during strong earthquakes, *Bulg.Geophys. J.* X **4**, 94–106.

Christoskov, L., Samardjieva, E., and Solakov, D.: 1990, Improvement of the approach in determining the possible human losses during strong earthquakes, *Bulg. Geophys. J.* XVI **4**, 85–92.

Ganse, R. A. and Nerlson, J. B.: 1981, *Catalog of Significant Earthquakes 2000 B.C.-1979*, World Data Group A for Solid Earth Geophysics, Boulder, Colorado, USA, Report SE-27.

Giardini, D., Jiménez, M. J., Grünthal, G., Sesame Working Group and ESC Working Group on Seismic Hazard Assessment: 2002, In: *12th European Conference on Earthquake Engineering*, London, Elsevier Science Ltd., paper 790.

Grandori, G., Drei, A., Perrotii, F., and Tagliani, A.: 1991, Macroseismic intensity versus epicentral distance: the case of Central Italy, *Tectonophysics* **193**, 165–171.

Gupta, I. N. and Nuttli O. W.: 1976, Spatial attenuation of intensities for central US earthquakes, *Bull. Seism. Soc. Am.* **66**, 743–751.

Institute of Geology and Geophysics (IGG): Chinese Academy of Sciences, Chaoyang District, P.O. Box 9825, Beijing 100029, China.

Instituto Geográfico Nacional (IGN): Ministerio de Fomento, General Ibáñez de Ibero 3, 28003 Madrid, Spain (http://www.ign.es).

Instituto Nacional de Estadística (INE): 2003, Ministerio de la Presidencia del Gobierno, Madrid, Spain (http://www.ine.es).

López-Casado, C., Molina, S., Delgado, J., and Peláez, J. A.: 2000a, Attenuation of intensity with epicentral distance in the Iberian Peninsula, *Bull. Seism. Soc. Am.* **90**, 34–47.

López-Casado, C., Molina, S., Giner, S. J., and Delgado, J. A.: 2000b, Magnitude-intensity relationship in the Ibero-Maghrebian region, *Nat. Hazards* **22**, 271–297.

Munich Reinsurance Group (MRG): 1999, *Topics 2000, Natural Catastrophes – The Current Position*, Munich, Germany, 126 pp.

Munich Reinsurance Group (MRG): 2000, *World Map of Natural Hazards* (CD-ROM), Munich, Germany.

Muñoz, D. and Udías, A.: 1987, Three large historical earthquakes in Southern Spain, In: J. Mezcua and A. Udías (eds), *Seismicity, Seismotectonic and Seismic Risk of the Ibero-Maghrebian Region*, Instituto Geográfico Nacional, Madrid, Monografía Num. 8, pp. 175–182.

Musson, R. M. W. and Winter, P. W.: 1997, Seismic hazard maps for the UK, *Nat. Hazards* **14**, 141–154.

National Earthquake Information Center (NEIC): US Geological Survey, Department of the Interior (http://neic.usgs.gov).

Ohta, Y., Goto, N., and Ohashi, H.: 1983, An empirical construction of equations for estimating number of victims by earthquakes, *Zisin II* **36**, 463–466.

Oike, K.: 1991, A discussion on the relation between magnitude and number of deaths by earthquakes, In: *Proc. Int. Seminar on Earthquake and Hazard Mitigation Technology*, Tsukuba, Japan, pp. 333–341.

Oike, K. and Hori, T.: 1998, History of Earthquakes and Seismic Disasters in East Asia, *Science* **68**, 409–415.

Papazachos, B. C., Papaioannou, Ch. A., Margaris, V. N., and Theodoulidis, N. P.: 1993, Regionalization of seismic hazard in Greece based on seismic sources, *Nat. Hazards* **8**, 1–18.

Payo, G., Canas, J. A., and Badal, J.: 1994, Seismic hazard and inelastic attenuation in the Iberian Peninsula, In: *Proc. US-Spain Workshop on Natural Hazards*, Barcelona, Spain, pp. 312–342.

Penn State University Libraries' Digital Chart of the World Server: 1992 (http://www.maproom.psu.edu/dcw).

Rodríguez de la Torre, F.: 1984, *Los terremotos alicantinos de 1829*, Instituto de Estudios Alicantinos, Alicante, Spain, serie I, número 100 (ISBN 84-505-0425-2).

Samardjieva, E. and Oike, K.: 1992, Modelling the number of casualties from earthquakes, *J. Nat. Disaster Sci.* XIV **1**, 17–28.

Samardjieva E., Payo, G., and Badal, J.: 1999, Magnitude formulae and intensity-magnitude relations for early instrumental earthquakes in the Iberian region, *Nat. Hazards* **19**, 189–204.

Samardjieva, E. and Badal, J.: 2002, Estimation of the expected number of casualties caused by strong earthquakes, *Bull. Seism. Soc. Am.* **92**, 2310–2322.

Shebalin, N. V.: 1985, Regularities of the natural disasters (in Russian), *Nauki o zemle*, Vol. 11, Znanie, Moscow, 48 pp.

Shedlok, K. M., Giardini, D., Grünthal, G., and Zhang, P.: 2000, The GSHAP Global Seismic Hazard Map, *Seism. Res. Lett.* **71**, 679–686.

Tilford, N. R., Chandra, U., Amick, D. C., Moran, R., and Snieder, F.: 1985, Attenuation of intensities and effect of local site conditions on observed intensities during the Corinth, Greece, earthquakes of 24 and 25 February and 4 March 1981, *Bull. Seism. Soc. Am.* **75**, 923–937.

Udías, A.: 1999, *Principles of Seismology*, Cambridge University Press, 475 pp.

Utsu, T.: 1988, Relation between seismic intensity near the epicenter, focal depth and magnitude (in Japanese), *Bull. Earthq. Res. Inst.* **63**, 23–31.

Utsu, T.: 1990, *Table of worldwide disastrous earthquakes* , Univ. Tokyo, Japan, 243 pp.

VanMarcke, E. H. and Shi-Sheng, P. L.: 1980, Attenuation of intensity with epicentral distances in the Philippines, *Bull. Seism. Soc. Am.* **70**, 1287–1291.

World Bank: 2003 (www.worldbank.org).