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Hazard Mapping Based on Macroseismic Data Considering the Influence of Geological Conditions

M. L. SOUSA[1] and C. S. OLIVEIRA[2,1]
[1]*Laboratório Nacional de Engenharia Civil; Lisbon, Portugal*
[2]*Instituto Superior Técnico; Lisbon, Portugal*

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Abstract. The object of this study is to consider directly the influence of regional geological conditions on the assessment of seismic hazard. It is assumed that macroseismic data at individual locations contain, in an average way, the influence of geological conditions.

A Data Base referring to 199 historical (5) and instrumental (194, in the 1947–1993 period) events with macroseismic information in 1195 locations of Portugal was built. For any given seismic event, whenever macroseismic information was available at a location (town, village, etc.), an EMS-92 intensity value was estimated. To each one of those locations a geological unit, representing the most common type of soil, was assigned, based on the Geological Portuguese Map at a scale 1:500 000; the geological units were grouped into three categories: soft, intermediate and hard soils.

The Data Base was used to determine the attenuation laws in terms of macroseismic intensity for the three different geological site conditions, using multiple linear regression analysis. The reasonability of the laws was tested by (i) checking residual distributions and (ii) comparing the map of isoseismals of important earthquakes with the isoseismals generated by the attenuation curves derived for each one of the three different soil classes, taking into consideration the soil class of each site. The main results of attenuation modeling are: high dispersion on macroseismic intensity data; all the models predict intensity values, for short hypocentral distances, lower than the ones observed; and for some important analyzed earthquakes and for the observed range of distances, the models confirm the expectancy that macroseismic intensity increases from hard to soft soil.

The approach to obtain the hazard assessment at each location consisted in the use of the attenuation law specifically derived for the class of soil of that particular location. This method, which considers the influence of the regional geology, was illustrated with the mapping of hazard for the country for several return periods. Comparison with previous maps not taking into consideration the regional geological conditions emphasizes the importance of this new parameter. It can be concluded that (i) soil segmentation is clearly the cause for hazard increase in the region to the north of Lisbon, especially at sites with soft and intermediate soils as the ones in lower Tagus valley; the maximum increase on hazard is, in any case, less than one degree; (ii) when geological conditions are disregarded in the attenuation regression analysis, hazard pattern is similar to the one obtained for the case of hard soil everywhere.

Key words: seismic hazard, geological conditions, attenuation laws, statistical analyses, Portugal.

1. Introduction

The influence of geological conditions is known to have a very important role in the determination of seismic input for engineering analysis. Locations that systematically have shown higher seismic intensities during past earthquakes, are probably connected with zones with higher amplifications due to softer geological substrata.

The influence of site conditions on peak ground acceleration or spectral ordinates has been studied in the past (Trifunac, 1990; Lee and Manic, 1994). In this paper attenuation laws on macroseismic intensity considering site conditions are examined and applied for hazard evaluation.

For a large number of past events the information on macroseismic intensities is available for many different sites where the geological conditions are known. This conditions are brought into this study by attaching to each site, where seismic intensity was observed during past earthquakes, a parameter characterizing the site geology into three categories. This set of data (intensities and geological site categories) allows the investigation on the influence of geological conditions on attenuation curves and, consequently, on hazard estimates.

This approach corresponds to an improvement with respect to the usual methodologies, because a new variable is considered in the study of the attenuation of macroseismic intensities, introducing a regional dependence on the estimation of intensities.

Multiple linear regression analysis was applied to derive attenuation laws for each soil category. Hazard mapping was obtained using the attenuation law specifically determined for the category of soil of each particular location and applying average matrix smoothing to the results.

Another way to consider the soil amplification would have been to evaluate the hazard for the whole region considering only the attenuation laws derived for hard rock sites and, subsequently, correcting that hazard through an amplification factor connected to the soil category. The amplification factor can be obtained from the average of intensity values of each soil category.

This work does not look at any detailed analysis of soil amplification as it is the case of a soil specific study. On the contrary, the soil influence on the attenuation of seismic waves is viewed at a regional scale.

2. Methodology

2.1. DATA ANALYSIS

The *Data Base on Macroseismic Information of Continental Portugal* (Paula, 1994; Oliveira *et al.*, 1995; Paula and Oliveira, 1995) stores, till now, macroseismic information on 199 earthquakes felt in Portugal, with known epicentre. From those 199 earthquakes, the greatest number (194) occurred between 1947 and 1993. The remaining earthquakes are large historical events identified on Table I.

The Data Base was built based on the tables EARTHQUAKE and SITES connected by the table INTENSITIES, that is, the effects of an *earthquake*, expressed by *intensities*, felt in several *sites*. These relations are schematized in Figure 1 and justified by the use of the Data Base in estimating attenuation laws.

Table I. Seismological parameters of historical events in the Data Base.

Date	Origin time	Lat. N	Long. W	Max. Int. (EMS-92)	Macroseismic magnitude
January 26, 1531	4–5 h	38.95°	9.00°	IX–X	7.0
November 1, 1755	9:40 h	36.00°	10.50°	–	8.5–8.8
March 19, 1858	13:30 h	41.20°	7.00°	VII	4.3
November 11, 1858	7:15 h	38.20°	9.00°	–	7.0–7.2
April 23, 1909	17:04:32 h	38.90°	8.77°	VIII–IX	6.9–7.0

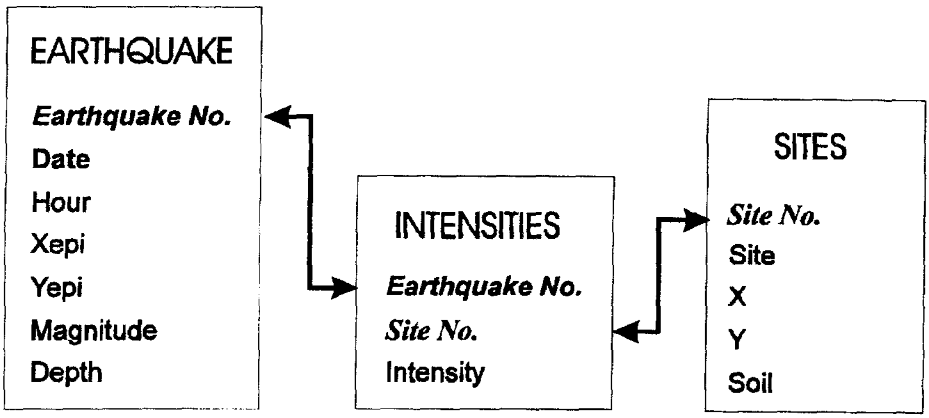

Figure 1. Logical scheme of the Data Base.

Figure 2 presents the distribution of epicentres and respective magnitude that fulfill table EARTHQUAKE.

The information contained in the table EARTHQUAKE refers mainly to weak earthquakes; more than 80% of the events have magnitudes between 3.0 and 5.0. In order to increase the range of magnitudes five historical events were added to the Data Base; one of them, the 1755 earthquake, also known as Lisbon earthquake, had an estimated macroseismic magnitude between 8.5 and 8.8, and an epicentral location at the Gorringe bank (see Table I).

Table INTENSITIES stores 3209 values of intensity felt in 1194 sites related to the 199 earthquakes recorded in the Data Base.

Historical events (Table I) are responsible for the largest macroseismic intensities stored in the Data Base. The worst event causing extremely large losses was the 1755 earthquake, producing an intensity varying between VIII and X EMS-92 scale, (Grünthal, 1993) in the town of Lisbon. Closer to the epicentre, in the Algarve, at the south of Portugal, due to the total destruction of the town of Lagos and Faro a macroseismic intensity of X EMS-92 was attributed. The same macroseismic intensity was assigned to the villages of Sagres, Lagoa, Silves and Portimão. Other historical events, namely the 1531 and 1909 earthquakes, caused great losses in

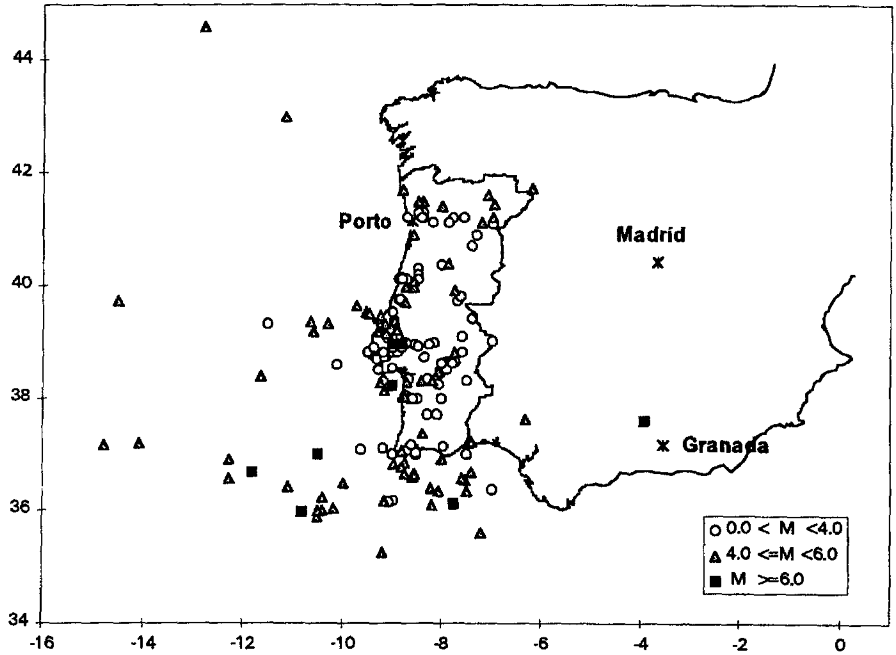

Figure 2. Spatial distribution of epicentres and magnitudes in the Data Base.

the lower Tagus valley, damaging the village of Benavente, situated 40 km NE of Lisbon. The first event was felt in Lisbon with intensity IX EMS-92.

The effects of the nonhistorical events, expressed as macroseismic intensities, do not exceed intensity IV in EMS-92 scale in 78% of the earthquakes. The remaining 22% produced damage in buildings located at one or more sites. For this period (1947–1993), the maximum intensity in the sample is VIII–IX* EMS-92 and was observed in Algarve as the result of the 1969 earthquake.

Table SITES includes 1194 sites (coordinates, X and Y) where earthquakes were felt; their spatial distribution is presented in Figure 3. The superficial geological conditions in each site were classified simply in three categories: *soft*, *intermediate* and *hard* soil, bearing in mind the Eurocode 8 (ENV, 1988-1-1, 1994) specifications, and the stratigraphic geological units. Roughly speaking, the *soft soil* corresponds to loose cohesionless alluvium of the Quaternary period; the *intermediate soil* corresponds to deposits of medium dense sand, gravel or medium stiff clays of the Cenozoic (Neogene) period; and the *hard soil* to rock or other hard and stiff deposits of sand, gravel or overconsolidated clay, of the early Cenozoic (Paleogene), Mesozoic, Paleozoic and Precambrian periods and also eruptive and metamorphic rocks. The assignment of the soil category to each site was based on the Geological Portuguese Map (DGMSG, 1972) at the scale 1:500 000.

* Whenever the macroseismic intensity is in between two degrees, Data Base assume the average.

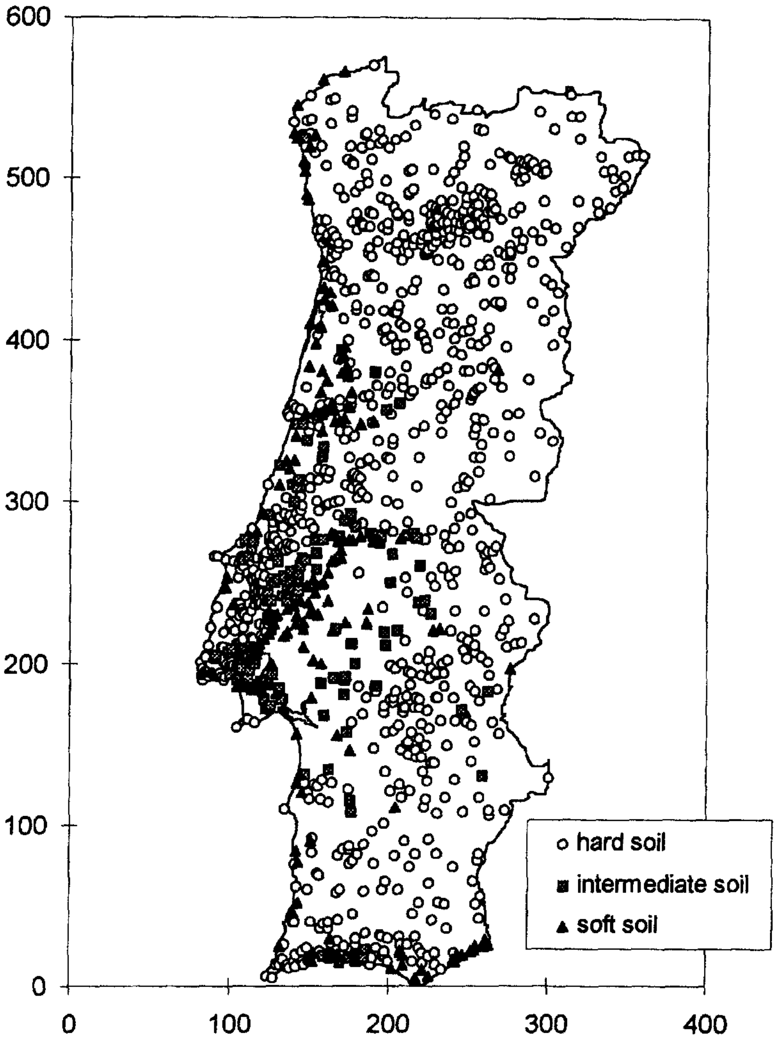

Figure 3. Spatial distribution of sites and respective soils in the Data Base.

This classification of site geology is also shown in Figure 3. Among the 3209 observations of intensities of the Data Base, the greatest number was assigned to sites with hard soil (69%) and the remaining are distributed by sites with intermediate soil (14%) and soft soil (17%). This last category shows a special incidence on lower Tagus valley, southern and western coast.

2.2. SEISMIC SOURCE MODEL

The model of 12 seismic source zones illustrated in Figure 4 follows the recent revision of the neotectonic map (Cabral, 1993), the distribution of historical and instrumental seismicity (Sousa *et al.*, 1992), and the principle of adjusting the zones to large geological units. This model is different from a previous one (Campos-Costa *et al.*, 1992) with 36 zones closely following the multiplicity of traces defining the geologic active (in the last 2 million years) structures. However, as it can be seen in Figure 4, seismicity in continental region is diffuse, showing little correlation with neotectonic structures. In consequence, broader areas were adopted. The model of the present paper is similar to the one presented by Oliveira *et al.* (1995) with the addition of two small zones where great concentration of seismicity has taken place in the past (source zones 5A and 6A). A detailed description and discussion of the seismic source model can be found in Sousa (1996). Note that 5–5A means zone 5 minus zone 5A; the same applies to zones 6 and 6–6A.

The decision to consider 12 zones to characterize both the occurrence and attenuation models was only based on seismotectonic evidence. The homogeneity of each zone in relation to the parameters of the probability distributions which characterize them, was not tested because this study does not intend to investigate the dependence of occurrence models on the geometry of the source zones. In relation to the attenuation models, as it is developed in Section 2.4.1, the role of tectonic zonation was investigated, in a simplified way, for two large regions grouping the 12 zones.

2.3. OCCURRENCE PROCESS

The process of seismic occurrence was based on data contained in the Seismic Catalogue of Iberian Peninsula (Sousa *et al.*, 1992).

The occurrence process in each source zone was characterized by the Poisson distribution and by the Gutenberg–Richter distribution of magnitudes. Details on seismic rates estimates, reliability of the assumption of the Poisson process, maximum magnitude for each source zone and the *b*-value of Gutenberg–Richter law, are not the object of this paper and can be found in Sousa *et al.* (1996). For reasons of completeness, a summary of the parameters of the occurrence process is presented in Table II. These are necessary inputs to the hazard estimate performed in Section 3.

2.4. STRONG GROUND MOTION PROCESS – MACROSEISMIC INTENSITY

Macroseismic intensity was chosen as the dependent variable in the attenuation model due to the scarcity of instrumental data in Portugal mainly for high magnitudes. The following model was adopted:

$$I = c_1 + c_2 \cdot M + c_3 \cdot \ln(R) + c_4 \cdot R \qquad (1)$$

where I is macroseismic intensity, M is local magnitude and R is hypocentral distance. Equation (1) can be deduced semi-empirically (Howell and Schultz,

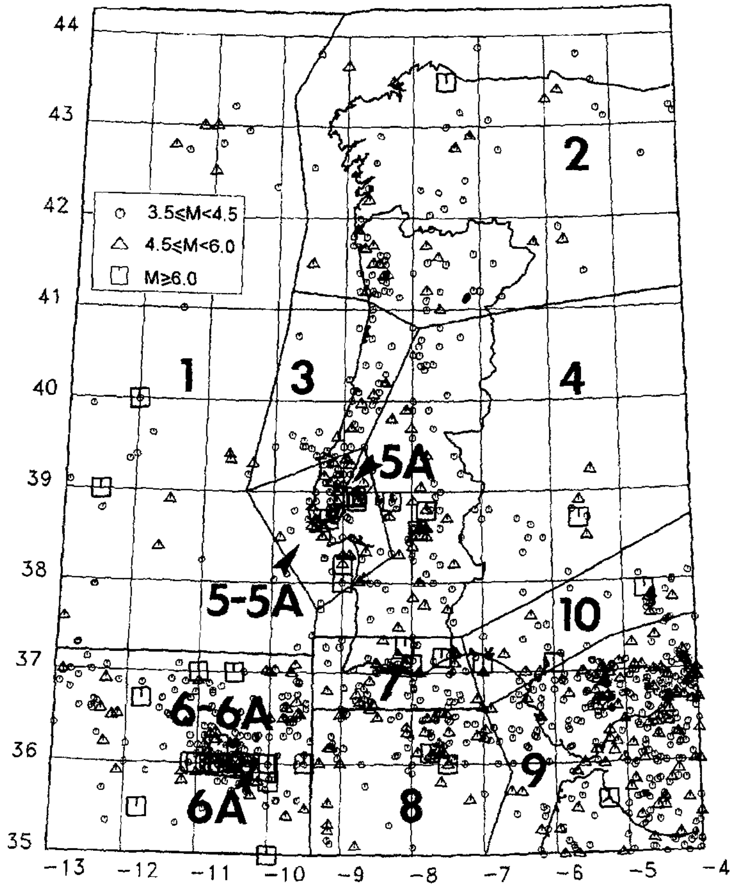

Figure 4. Earthquake epicentres, 33 AD-1991, $M \geq 3.5$ (Sousa *et al.*, 1992) and seismic source model (Sousa, 1996).

1975); there, the coefficient c_3 is related to the geometric attenuation and c_4 to the quality factor. This equation is also suitable for large and short epicentral distances.

Even though macroseismic intensity is defined as a discrete ordinal variable (Grünthal, 1993), it is assumed in this paper, for statistical analysis, that intensity is measured in a continuous interval scale. This assumption would have been overcome if intensities were transformed into peak ground acceleration or velocity and the attenuation modeling was performed with these variables.

Several attempts were made to fit Equation (1) to the data in the Data Base. The first one was to try an attenuation curve to each delineated source zone, with the exception that a single model was used in zones 5A and 5–5A using the data of the two zones together (the same applies to zones 6A and 6–6A).

However, as attenuation models are estimated with the information existing in the Data Base and, consequently, limited to its magnitude range, an extrapolation

Table II. Maximum magnitude, number of earthquakes per year, estimates of *b*-value of the Gutenberg-Richter law.

Source zone	M_{max}	No.earthq./year	*b*-value
1	7.0	0.50	−0.6636
2	6.0	1.14	−0.8415
3	5.6	0.54	−0.8940
4	7.0	1.37	−0.8370
5–5A	7.2	0.70	−0.9497
5A	7.0	0.26	−0.7585
6–6A	6.6	1.59	−0.6442
6A	8.5	0.71	−0.3373
7	7.8	0.77	−0.9213
8	7.1	0.86	−0.6431
9	6.2	3.97	−1.2233
10	7.0	0.57	−0.8664
Background seismicity	3.5	14.92	−1.3879

Table III. Maximum magnitude in the Seismic Catalogue and Data Base.

Source zone	Catalogue maximum magnitude	Data Base maximum magnitude
1	7.0	4.8
2	6.0	5.2
3	5.6	5.2
4	7.0	4.8
5	7.2	7.2
6	8.5	8.5
7	7.8	5.2
8	7.1	7.1
9	6.2	–
10	7.0	–

process to higher magnitude range would be necessary in order to perform the hazard evaluation, which requires the knowledge in the range of magnitudes registered in the Seismic Catalogue. Table III compares maximum magnitude reported in the Seismic Catalogue (Sousa *et al.*, 1992) and in the Data Base (Paula, 1994; Paula and Oliveira, 1995; Oliveira *et al.*, 1995).

Although five severe historical earthquakes were added to the Data Base, maximum magnitudes existing in the Catalogue are, as a general rule, greater than the maximum magnitudes observed in the Data Base. The main reason for the above mentioned discrepancy relies on the fact that the Catalogue covers a time period of approximately 2,000 years while the Data Base only covers, exhaustively, the period of the last 50 years. Source zones 5, 6 and 8 are the exceptions because they contain the historical earthquakes added. The Data Base does not contain any information in source zones 9 and 10 (zones outside Portugal).

In order to overcome the attempt to fit a single model to each zone, the modeling strategy included two type of data segmentation, justified in the following sections.

2.4.1. *Source Segmentation*

Lack of magnitude data in high ranges, made clear by Table III, imposed the grouping of data of a few zones to avoid the extrapolation of the attenuation models into ranges of magnitudes not observed. The grouping criteria was related to the two main physical mechanisms of earthquake generation existing in Portugal. There are interplate events (mainly in zones 1, 6, 8 and 9) with high magnitude, long duration and low frequency content, and intraplate events (mainly in zones 2, 3, 4, 5, 7 and 10) with smaller magnitude, shorter duration and lower frequency content. Due to this specific seismic character of Portuguese region, the following options were adopted:

(i) source zones 5, 6 and 8 have their own laws;
(ii) in source zones 2, 3, 4, 7 and 10, the available data of intraplate sources was used, that is, the data of source zones 2, 3, 4, 5 and 7 were grouped (intraplate model);
(iii) in source zones 1 and 9 the available data of interplate sources was used, that is, the data of source zones 1, 6 and 8 were grouped (interplate model).

To check the statistical significance of the influence of the two main seismic source mechanisms on the response variable (*macroseismic intensity*), an analysis of covariance was applied. Macroseismic intensity was related to a nominal variable, *source* (intraplate or interplate), while the two controlled continuous covariates were *local magnitude* and *hypocentral distance*.

The null hypothesis *source does not influence intensity*, tested at a 5% significance level, was rejected and one may conclude that there is a significant difference between the influence of the two source mechanisms on macroseismic intensity.

2.4.2. *Soil and Source Segmentation*

The explicit influence of site conditions could be considered in Equation (1), with the inclusion of two additional dichotomous variables representing the three categories of soil. This formulation was not followed, because the available hazard algorithm (McGuire, 1976) required a few modifications prior to its use, and the inclusion of this two additional variables in the model is difficult to justify in physical terms. However, the soil influence was taken into account segmenting the data by soil classes and three attenuation models were fitted for each group of zones.

Table IV. Average value of macroseismic intensities for each soil category and results of multiple range Scheffe tests.

Soil	Interplate earthquakes				Intraplate earthquakes		
	Intensity[a] average	Homogeneous groups			Intensity average	Homogeneous groups	
Hard	4.7	*			3.7	*	
Intermediate	4.9	*	*		4.1		*
Soft	4.9		*		4.2		*

[a] Note that for statistical analysis, macroseismic intensity is assumed as a continuous variable.

To check the statistical significance of the influence of the nominal variable *soil* on the response variable (*macroseismic intensity*), an analysis of covariance was applied. This procedure allows to isolate the variance in the response variable (*macroseismic intensity*) due to other variables different from the *soil*: the controlled continuous covariates were again *local magnitude* and *hypocentral distance*.

The null hypothesis *soil does not influence intensity*, tested separately for intraplate and interplate data at a 5% significance level, was rejected and one may conclude that there is a significant difference between the influence of the three types of soils on macroseismic intensity, for both source mechanisms.

Table IV displays a multiple range analysis for macroseismic intensity averages at each category of soil. The Scheffe range test was used at a confidence level of 95%.

This table allows a concise picture of the influence of source mechanism and soil:

(i) when interplate earthquakes are analyzed there are two possible homogeneous groups of soils in terms of their effects on macroseismic intensity; the group of hard-intermediate soils and the group of intermediate-soft soils (one group for each column of asterisks);

(ii) when intraplate earthquakes are analyzed there is one possible homogeneous group of soils in terms of its effects on macroseismic intensity, the group of intermediate-soft soils.

2.4.3. *Attenuation Modeling*

The parameters of the attenuation model are estimated by multiple regression analysis based on the *Data Base on Macroseismic Information of Continental Portugal* (Paula, 1994; Oliveira *et al.*, 1995; Paula and Oliveira, 1995).

Multiple regression was performed for five different situations: source zones 5, 6 and 8, intra and interplate earthquakes, each one considering soil segmentation (see Table V). Attenuation not considering the soil segmentation was also obtained for each one of the five situations above (line 'all' in Table V). Table V also shows the number of pairs *hypocentral distance – intensity* (the values presented in lines 'all' equal the sum of the values presented in lines 'hard', 'intermediate' and 'soft') and the number of different observations of the independent variable *magnitude* used in the regression. The same earthquake can be observed in a set of sites where the three, the two or just one type of soil are present. Only the pairs *hypocentral distance – intensity* in line 'all' should equal the sum of 'hard', 'intermediate' and 'soft'. The number of different observed magnitudes in line 'all' must be greater than, or equal to the maximum number of observed different magnitudes in sites with hard, intermediate or soft soil. Magnitude range, standard error of regression and adjusted determination coefficient R^2 are also shown in Table V. Symbol 'ns' indicates that the result of t test (H_0: $c_i = 0$) is not statistically significant at level of 5%. In those cases regressions were made again without considering the correspondent variable.

Figure 5 illustrates the observed (symbols) versus predicted (lines) values for the observations of the events that, in the source zones 5, 6 and 8, have the greatest number of intensity observations, that is, the 1755 earthquake in source region 6, the 1909 earthquake in source region 5 and the 1964 earthquake in source region 8.

From Figure 5 the following can be emphasized:

(i) high dispersion on intensity data is evident in those figures;
(ii) generally the models predict intensity values, for short hypocentral distances, lower than the ones observed;
(iii) for the earthquakes analyzed and for the observed range of distances, the models confirm the expectancy that macroseismic intensity increases from hard to soft soil;
(iv) the model for zone 6 does not predict well the intensities observed in 1755, showing lower values at 'short' distances (200 km) and higher at long distances.

One way to judge the quality of the attenuation models is to study the frequency distribution of regression residuals. For illustration, Figure 6 presents this distribution for zone 5 attenuation model, hard soil, and Figure 7 compares theoretical vs. observed site intensities for the same relationship.

For this zone (and from Figures 6 and 7) it follows that residuals fit to a normal distribution (a significance level of 1% for Chi-square test and of 5% for Komolgorov-Smirnov test) with a zero mean and a standard deviation of 0.88, and, again, the model predicts an intensity range narrower than the one observed, specially for larger intensity values.

A similar analysis for other soil models in zone 5 leads to residuals with larger scatter ($\sigma = 0.90$ for intermediate soils and $\sigma = 1.00$ for soft soils), rejects normality hypothesis but, again, the models predict intensity values lower than the ones observed.

Table V. Coefficients of attenuation models for seismic source zones 5, 6, 8, intraplate and interplate zones with segmentation by soil classes.

Data zone	Data soil	Obs. no int. – dist.	Obs. no magnitude	Magnitude range	c_1	c_2	c_3	c_4	Standard error	Adjusted R^2 (%)
5	all	854	11	3.0–7.2	0.9824	0.8554	−0.2335	−0.0064	1.09	35.7
	hard	587	10	3.0–7.2	1.6983	0.7700	−0.2999	−0.0069	0.71	44.2
	interm.	132	9	3.0–7.2	2.5552	0.8978	−0.8404	ns	0.91	55.5
	soft	135	8	3.6–7.2	ns	1.2102	−0.4700	−0.0064	1.01	66.1
6	all	578	11	4.1–8.5	7.7988	1.3376	−2.0167	ns	0.76	74.8
	hard	401	10	4.1–8.5	8.2329	1.2529	−1.9995	ns	0.75	73.0
	interm.	72	8	4.5–8.5	4.1466	1.4592	−1.5493	ns	0.63	82.8
	soft	105	6	4.5–8.5	7.1649	1.4794	−2.0300	ns	0.79	78.5
8	all	213	10	4.2–7.1	3.7374	0.7967	−0.8671	ns	0.61	50.8
	hard	132	9	4.2–7.1	3.9522	0.7811	−0.8928	ns	0.59	53.3
	interm.	20	6	4.2–7.1	ns	0.6141	ns	ns		
	soft	61	8	4.2–7.1	3.4291	0.8317	−0.8306	ns	0.68	40.2
intra-plate	all	1753	19	3.0–7.2	1.8819	0.7613	−0.3509	−0.0047	0.84	48.1
	hard	1227	19	3.0–7.2	1.8479	0.6384	−0.1870	−0.0053	0.80	36.0
	interm.	225	18	3.0–7.2	2.9206	0.8010	−0.7568	ns	0.84	58.2
	soft	301	18	3.0–7.2	ns	1.0583	−0.1672	−0.0080	0.89	66.1
inter-plate	all	917	19	3.6–8.5	ns	1.1625	−0.2682	−0.0035	0.85	70.5
	hard	625	18	4.1–8.5	−0.8703	1.0826	ns	−0.0041	0.83	67.7
	interm.	111	14	3.6–8.5	ns	1.2827	−0.3608	−0.0043	0.80	77.8
	soft	181	16	4.1–8.5	−2.2724	1.3566	ns	−0.0046	0.85	76.7

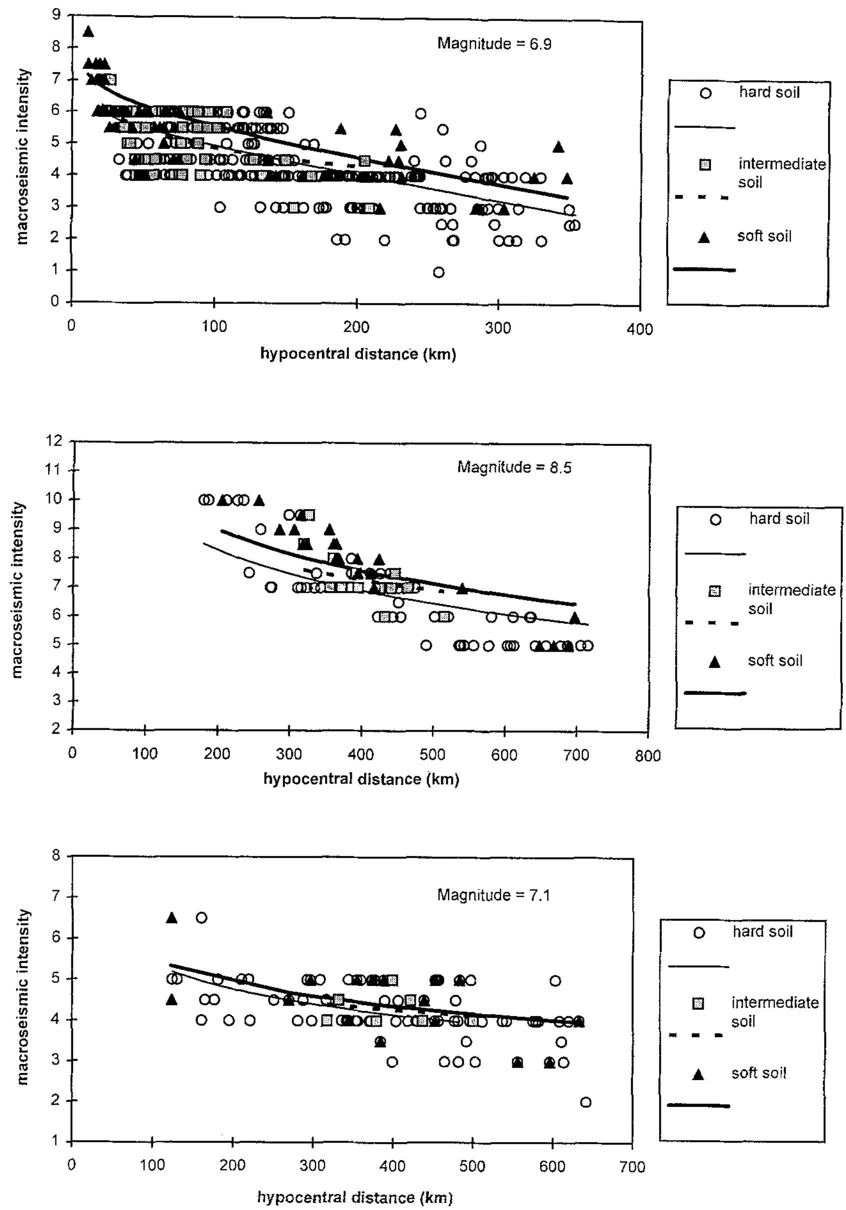

Figure 5. Observed intensities and attenuation model for three events; (a) 23 April 1909 Benavente earthquake and zone 5 model; (b) 1 November 1755 Gorringe earthquake and zone 6 model; (c) 15 March 1964 earthquake and zone 8 attenuation model.

Another way to judge the quality of fitting of the attenuation models is through confrontation of the predicted isoseismals with isoseismals of real earthquake of the same magnitude. Figure 8 illustrates that comparison presenting, in pairs, isoseismals of 1909, 1755 and 1964 earthquakes obtained from observed intensities

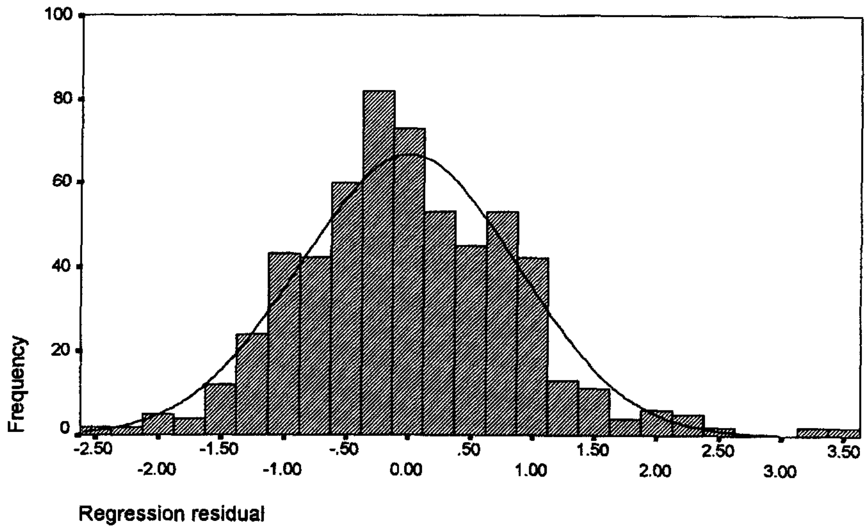

Figure 6. Histogram of regression residuals; zone 5 attenuation model, hard soil.

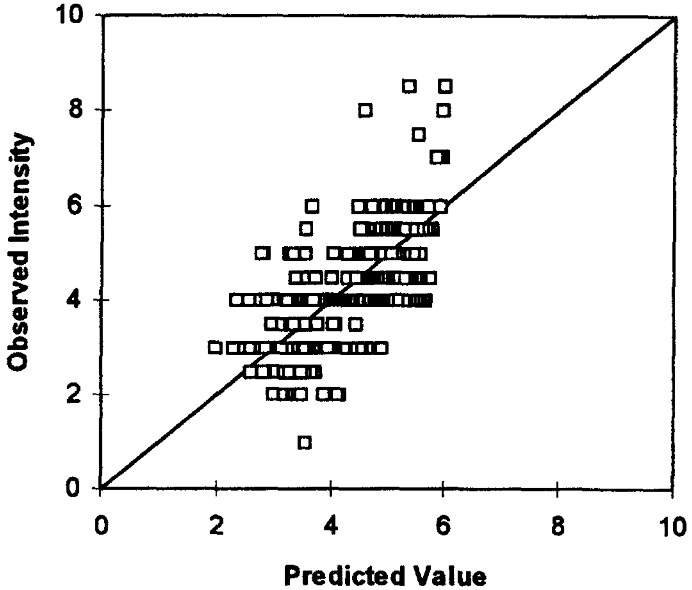

Figure 7. Predicted values by zone 5 attenuation model, hard soil, vs. observed site intensities.

and isoseismals generated by the attenuation models of correspondent source zones and magnitudes. In each site where observed intensity values are available, the attenuation model corresponds to the category of soil of that site. If segmentation by soil classes was not considered the predicted isoseismals should be simple circumferences centered on the epicentre.

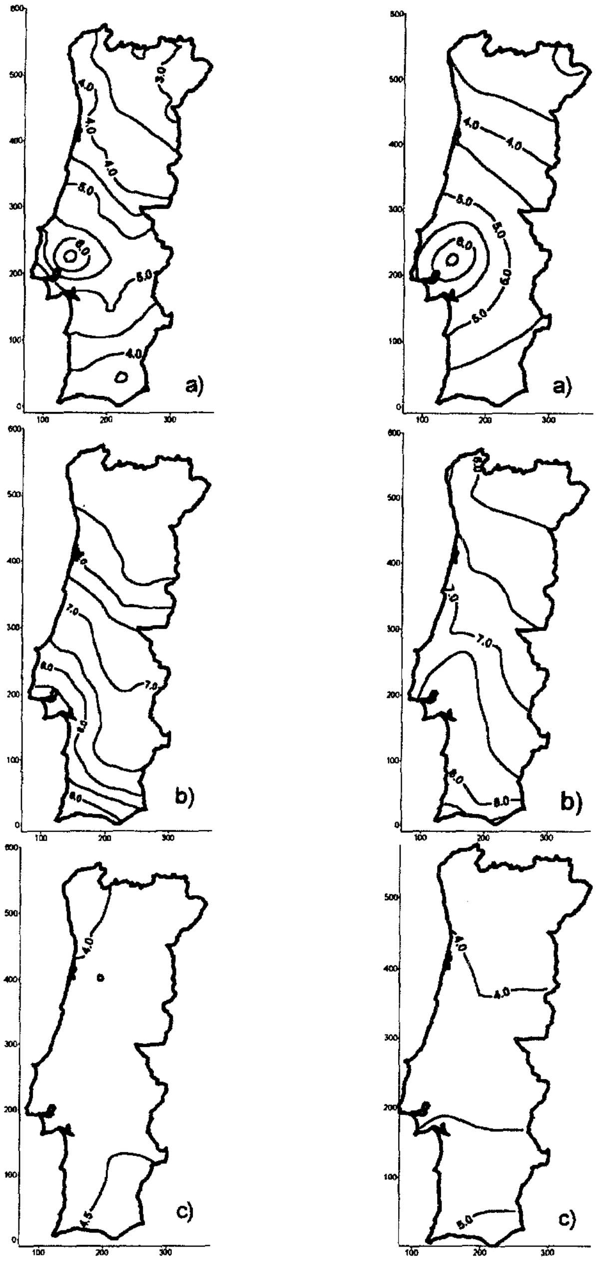

Figure 8. Comparison of isoseismals obtained with observed data (left) and attenuation model (right) (a) 23 April 1909, (b) 1 November 1755, and (c) 15 March 1964.

The comparison between the observed and simulated isoseismals shows the following features:

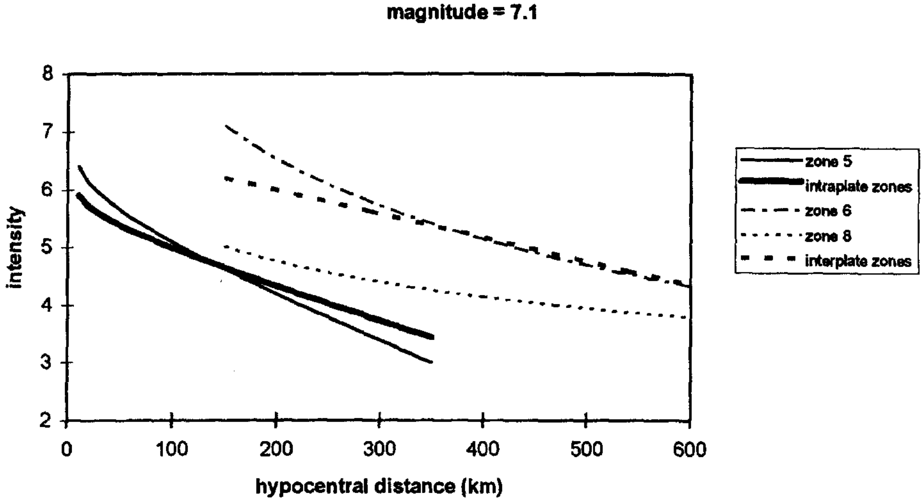

Figure 9. Comparison between attenuation laws for a fixed magnitude and hard soil.

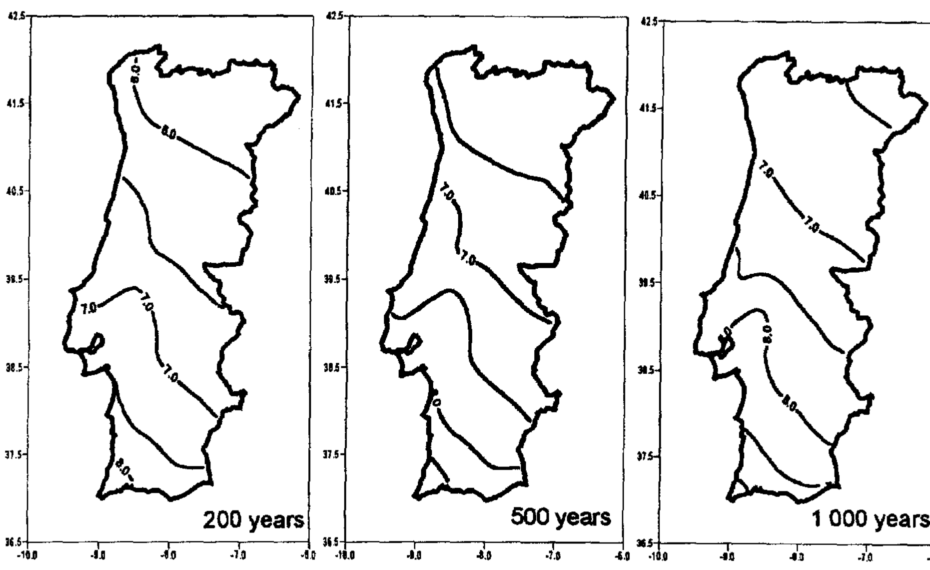

Figure 10. Seismic hazard maps for 200, 500 and 1,000 years return period and soil segmentation.

(i) for the 1909 earthquake a good agreement was obtained;

(ii) for 1755 the decrease in intensities from south to north is higher for the observed data than for zone 6 isoseismal model, as referred above;

(iii) for 1964 earthquake the attenuation of intensities is small both for observed data and for zone 8 isoseismal model.

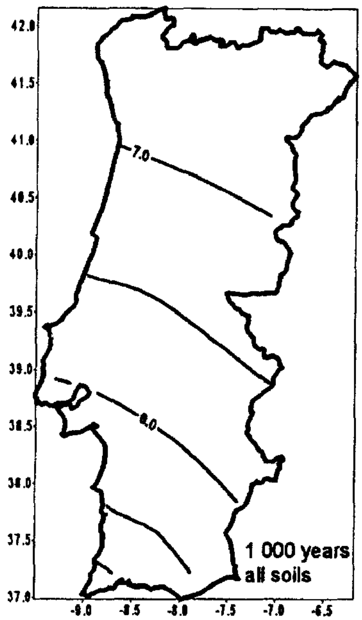

Figure 11. Seismic hazard map for 1,000 years return period without soil segmentation (left) and considering only hard soil attenuation law (right).

Figure 9 shows a comparison between attenuation laws (hard soil only) for different source zones ($M = 7.1$). In the figure only the range of hypocentral distances used in hazard analysis for Portugal is drawn, interplate attenuation refers to large distances, whereas intraplate distances are shorter. Attenuation models obtained for interplate zones always give higher intensity values, for the same distances, than intraplate models.

An excellent agreement for the attenuation laws between zone 5 (Benavente) and all other intraplate zones can be observed. Figure 9 also emphasizes a low attenuation decay for interplate, 6 and 8 zones, a good agreement between zone 6 (Gorringe) and interplate zones, but a discrepancy on the attenuation law for zone 8. If the discrepancy is not due to an overestimation of the magnitude of 1964 event, then it means that zone 8 can be considered as characterized by attenuation different from other interplate zones. In fact, a 7.1 local magnitude is assigned to this event in the Seismic Catalogue (Sousa *et al.*,1992), and its epicentre (7.75 W, 36.13 N) is reported as relatively close to the Portuguese southern coast.

As a final note one should add that the large scatter in macroseismic data overshadows (i) more refined modeling for the attenuation such as alternative forms to Equation (1) and (ii) loss of accuracy in statistical analysis. This can only be solved by increasing the Data Base prior to 1947 and by including instrumental data when available, especially from higher magnitude events.

3. Hazard Results and Discussion

Figure 10 presents the hazard maps for 200, 500 and 1000 year return periods considering soil segmentation.

Figure 11 presents the hazard map for 1000 year return period for: in the left, not considering soil segmentation (attenuation models identified by 'all' in Table 5) and in the right, considering only hard soil attenuation law (bed rock) everywhere. The two maps of Figure 11 were prepared to see the influence of soil conditions on the hazard maps, and the one on the right-hand side was drawn to give the possibility to perform site specific studies. From comparison of maps in Figures 10 (right) and 11, it is observed that soil segmentation is clearly the cause for hazard increase in the region to the north of Lisbon, especially at sites with soft and intermediate soils as the ones in lower Tagus valley (Figure 3); the maximum increase on hazard is, in any case, less than one degree.

When soil segmentation is put aside (Figure 11 left), i.e., when geological conditions are disregarded on the attenuation regression analysis, hazard pattern is similar to the one obtained in the case of hard soil everywhere (Figure 11 right), but with slightly higher hazard values. This result is expected, because in the case that soil conditions are averaged out (Figure 11 left), greater weight is given to hard soil sites which are considerably more numerous than the others.

Hazard maps with soil segmentation have a similar shape to the predicted isoseismals of the 1755 earthquake (Figure 8b right); the 500 years return period is the one that more closely resembles zone 6 model. One may conclude that the hazard in Portugal, for this return period, is mainly controlled by seismicity originated in source zone 6, with a clear influence of 1755 earthquake, responsible for the maximum magnitude in that zone.

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References

Cabral, J.: 1993, Neotectónica de Portugal Continental, PhD thesis, Lisbon University, Lisbon.

Campos-Costa, A., Oliveira, C. S., and Sousa, M. L.: 1992, Seismic hazard-consistent studies for Portugal, *Proc. 10th World Conference on Earthquake Engineering*, Madrid. Balkema, Rotterdam, pp. 477–482.

DGMSG – Direcção Geral de Minas e Serviços Geológicos: 1972, *Carta Geológica de Portugal. 1: 500 000*, 4th edn, coordinated by Carlos Teixeira, Lisbon.

ENV 1988-1-1: 1994, *Eurocode 8 – Design Provisions for Earthquake Resistance of Structures – Part 1 - 1: General Rules – Seismic Actions and General Requirements for Structures*, CEN, Brussels.

Grünthal, G. (Ed.): 1993, European Macroseismic Scale 1992 (up-dated MSK-scale), *Conseil de l'Europe. Chaiers du Centre Européen de Géodynamique et de Sismologie*, Vol. 7, Luxembourg.

Howell, B. F. and Schultz, T. R.: 1975, Attenuation of modified mercalli intensity with distance from the epicentre, *Bull. Seismol. Soc. Am.* **65**(3), 651–665.

Lee, V. W. and Manic, M.: 1994, Empirical Scaling of Response Spectra in Former Yugoslavia, *Proc. 10th European Conference on Earthquake Engineering*, Vienna, Balkema, Rotterdam.

McGuire, R. K.: 1976, EQRISK, Evaluation of Earthquake Risk to Site. Open File Report 76-67, United States Department of the Interior Geological Survey.

Oliveira, C. S., Campos-Costa, A., Sousa, M. L., Martins, A., Paula, A., Guedes, J., and Lucas, A.: 1995, *Estimativa dos Danos Causados por Sismos no Parque Habitacional do Continente Português. Contribuição para a Definição de uma Política de Seguros*, Study for the Associação Portuguesa de Seguradores, Lisbon.

Paula, A.: 1994, Avaliação de Informação Macrossísmica dos Sismos Sentidos em Portugal Continental no Período 1947–1993. Estudos de Atenuação, Graduation thesis, Faculty of Sciences, Lisbon University, Lisbon.

Paula, A. and Oliveira, C. S: 1995, Evaluation of 1947–1993 macroseismic information in Portugal using EMS-92 Scale, Paper submitted for publication in *Annali di Geofisica.*

Sousa, M. L.: 1996, Modelos Probabilistas para a Avaliação da Casualidade Sísmica em Portugal Continental, MSc thesis, Lisbon Technical University, Lisbon.

Sousa, M. L., Martins, A., and Oliveira, C. S.: 1992, Compilação de Catálogos Sísmicos da Região Ibérica, Report 36/92 – NDA, Laboratório Nacional de Engenharia Civil, Lisbon.

Sousa, M. L., Oliveira, R. C., and Oliveira, C. S., 1996, Análise Probabilista da Casualidade Sísmica em Portugal Continental, Paper presented at the 7th Congress of APDIO (Portuguese Association for the Development of Operational Research), Aveiro, Portugal, and submitted for publication at *Investigação Operacional.*

Trifunac, M. D.: 1990, How to model amplification of strong ground motion by local soil and geological site conditions, *Earthq. Engi. Struct. Dynam.* **19**(6), 833–846.