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ORIGINAL RESEARCH PAPER

Ground motion scenarios consistent with probabilistic seismic hazard disaggregation analysis. Application to Mainland Portugal

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Abstract Probabilistic seismic hazard for Mainland Portugal was re-evaluated in order to perform its disaggregation. Seismic hazard was disaggregated considering different spaces of random variables, namely, univariate conditional hazard distributions of M (magnitude), R (source-to-site distance) and ε (deviation of ground motion to the median value predicted by an attenuation model), bivariate conditional hazard distributions of M–R and X–Y (seismic source latitude and longitude) or multivariate conditional hazard distributions of M–R–ε and M–(X–Y)–ε. The main objective of the present work was achieved, as it was possible, based on the modal values of the above mentioned distributions, to characterize the scenarios that dominate some seismic hazard levels of the 278 Mainland Portuguese counties. In addition, results of 4D disaggregation analysis, in M–(X–Y)–ε, pointed out the existence of one geographic location shared by the dominant scenario of most analyzed counties, especially for hazard levels correspondent to high return periods. Those dominant scenarios are located offshore at a distance of approximately 70 km WSW of S. Vicente cape. On the other hand, the lower the return period the higher is the number of modal scenarios in the neighbourhood of the analyzed site. One may conclude that modal scenarios reproduce hazard target values in each site with great accuracy enabling the applications derived from those scenarios (e.g. loss evaluation) to be associated to a hazard level exceedance probability.

Keywords Hazard disaggregation · Seismic hazard · Mainland Portugal · Modal values · Seismic scenarios

1 Introduction

Earthquake scenarios are used in different domains of activities like civil protection disaster preparedness, loss modelling or seismic design, where deterministic events are required to

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evaluate dynamic time history analysis. However, the choice of an earthquake scenario is often based on heuristic assumptions, for example, the worst historical event reported in the menaced region.

The purpose of this work is to overcome the disadvantages of deterministic approaches, in what concerns the choice of earthquake ground motion scenarios, by means of a probabilistic seismic hazard disaggregation analysis.

According to McGuire (1995) when a probabilistic seismic hazard analysis (PSHA) is performed, all possible seismicity contributions to a site are integrated, and the concept of a single event threat for that site is lost. Consequently, in scenario studies the evaluation of a maximum probable or credible earthquake is often based on deterministic assumptions, like the magnitude of the worst historical event reported and its best guessed location derived from known geological faults, or seismic source zones.

In fact, the selection of a deterministic scenario is rarely based on an objective criterion. Moreover, the selection of a unique earthquake scenario disregards the concept of uniform risk level and doesn't guarantee an equal seismic protection for the all region under analysis.

To overcome the disadvantages of a deterministic analysis, one may derive a seismic scenario consistent with the results of a PSHA for a site, by means of a disaggregation analysis. This method was applied to estimate seismic scenarios that control hazard at a site and it was found that, the ground motion derived from those scenarios may be used to reproduce the hazard target levels, in that site, with great accuracy. Although a wide range of applications are possible, present scenarios studies were developed with the ultimate goal of being applied to seismic risk regional analysis.

2 Overview of seismic hazard disaggregation analysis

According to Montilla (2000) the first author to perform a seismic disaggregation process was Bernreuter (1992) intending to determine a controlling earthquake from a PSHA, that is, the earthquake that most significantly contributes, in terms of magnitude and distance to the hazard at a site, for a given hazard level.

Although this analysis is somehow recent, it has been extensively discussed and applied, namely by Bazzurro (1998), Bazzurro and Cornell (1999), Campos Costa et al. (2002), Carvalho et al. (2002), Chapman (1995), Cramer and Petersen (1996), Frankel et al. (1996), Frankel et al. (2000), Harmsen and Frankel (2001), Harmsen et al. (1999), McGuire (1995), Montilla (2000), Montilla et al. (2002), Sousa (2006), Sousa and Campos Costa (2006), Sousa and Carvalho (2001) and Sousa et al. (2001). Also some technical books (e.g. Kramer 1996; Pinto et al. 2004) address the theme, even though briefly.

Seismic hazard disaggregation consists in the separation of the hazard exceedance contributions in different spaces of bins of the random variables of the process. The most used bin space is bi-dimensional (2D); that is, the relative contribution to the hazard is studied in terms of elementary bins of magnitude M, and of earthquake to site distance R or ln R. McGuire (1995) included a third dimension in the procedure, analyzing the contribution to the hazard of 3D bins in M–R–ε. The variable ε, representing the third dimension referred above, is a measure of ground motion randomness. Bazzurro and Cornell (1999) improved the disaggregation process evaluating hazard contributions in terms of M and ε and latitude and longitude, or Cartesian coordinates (X, Y), instead of R. These authors pointed out that seismic hazard may be disaggregated in spaces of random variables with different dimensions, for instances, contributions to hazard may be accumulated in one-dimensional bins of magnitude M or of distance R, in bi-dimensional M–R bins, or in multi-dimensional M–R–ε bins.

Bazzurro and Cornell (1999) called these procedures 1D, 2D and 3D hazard disaggregation techniques, respectively.

Defining the seismic hazard disaggregation procedure, Bazzurro and Cornell (1999) explain that a disaggregation process initially evaluates the mean annual frequency of exceedance of a hazard level h, $\lambda_{H>h}$, at a site, located in a region characterized by N_Z seismic source zones identified by the index k:

$$\lambda_{H>h} = \sum_{k=1}^{N_Z} \nu_k \cdot \int_M \int_R \int_\varepsilon \mathcal{H}[H(M, R, \varepsilon)_k - h] f_M(m)_k f_R(r)_k f_\varepsilon(\varepsilon)_k \mathrm{d}\varepsilon \mathrm{d}r \mathrm{d}m \tag{1}$$

where ν_k is the mean annual rate of earthquake occurrence with $M > m_{\text{mink}}$ in a source zone k, with a m_{mink} specified lower bound magnitude. $\mathcal{H}[H(M, R, \varepsilon)_k - h]$ is the Heaviside function assuming the null value, if $H(M, R, \varepsilon)_k$ is less then h, and the unit value otherwise and $f(\cdot)_k$ is the probability density function of source zone k of the considered random variables, admitted statistically independent.

According to Bazzurro and Cornell (1999) the disaggregation of hazard can be achieved in two steps: (i) to accumulate in each bin its contribution to the global hazard and (ii) to divide the contribution accumulated in each bin by the total annual frequency of exceedance $\lambda_{H>h}$:

$$f_{M,R,\varepsilon}(m, r, \varepsilon|H > h) = \frac{\sum_k \nu_k \cdot \mathcal{H}[H(M, R, \varepsilon)_k - h] f_M(m)_k f_R(r)_k f_\varepsilon(\varepsilon)_k}{\lambda_{H>h}} \tag{2}$$

Therefore, hazard disaggregation represents a conditional probability that, given the exceedance of a specified ground motion level, has been caused by a certain combination of M and R and ε (McGuire 1995). In other words, when the contribution to hazard is accumulated in a 3D bin, of M, R and ε, the disaggregated hazard is represented by the probability distribution of M, R and ε, conditional on $H > h$ at the site (Bazzurro and Cornell 1999).

Bazzurro and Cornell (1999) also emphasize that when the aim of a disaggregation procedure is to investigate what are the seismic scenarios that cause the exceedance of the specified ground-motion level at the site, the results of hazard disaggregation are often summarized into measures of central tendency like means or modes. Discussion on whatever an earthquake scenario should be defined by a pair of mean values $(\bar{M}, \bar{R})$ or by a pair of modal values $(\hat{M}, \hat{R})$ resulting from hazard disaggregation, has taken place. Harmsen et al. (1999) decided on computing both mean and modal values, pointing out that the use of $(\hat{M}, \hat{R})$ can be dependent on the dimension of the bins, whereas the use of $(\bar{M}, \bar{R})$ may correspond to scenarios with negligible contribution to the hazard.

Montilla et al. (2002) support that the existence of significant differences between mean and modal values reveals that seismic source zones affecting a site are multiple.

The disaggregation in 1D and 2D bin spaces is associated to marginal probability density functions (*pdf*) conditional on the exceedance of a hazard level h, that can be derived from Eq. 2. For instance, the conditional marginal *pdf* of M and ε are, respectively, defined by:

$$f_M(m|H > h) = \int_R \int_\varepsilon f_{M,R,\varepsilon}(m, r, \varepsilon|H > h) \mathrm{d}\varepsilon \mathrm{d}r \tag{3}$$

$$f_\varepsilon(\varepsilon|H > h) = \int_M \int_R f_{M,R,\varepsilon}(m, r, \varepsilon|H > h) \mathrm{d}r \mathrm{d}m \tag{4}$$

and the marginal probability joint distribution of M and R, conditional on the exceedance of a hazard level h, is defined by:

$$f_{M,R}(m, r|H > h) = \int_{\varepsilon} f_{M,R,\varepsilon}(m, r, \varepsilon|H > h)\mathrm{d}\varepsilon \tag{5}$$

Bazzurro and Cornell (1999) improved the disaggregation procedure evaluating the relative contribution to hazard levels, not only in a bin space of M, R and ε, but also considering the variables latitude and longitude instead of R, introducing a 4D disaggregation analysis with the variables M–(X, Y)–ε.

Those authors proposed the so called geographic disaggregation, where the variable R is generalized to a bi-dimensional random vector, $\mathbf{R} \equiv (X, Y)$, representing the distance between the site and the centre of the cell where the contribution to hazard is being accumulated. This technique has the advantage of being presented in a map that includes the studied site, contributing to the identification of sources that control that site hazard (Bazzurro and Cornell 1999).

Formally, the marginal joint distribution of (X, Y), or of the random vector $\mathbf{R}$, conditional on the exceedance of a hazard level h, is defined by:

$$f_{X,Y}(x, y|H > h) = \int_{M}\int_{\varepsilon} f_{M,(X,Y),\varepsilon}(m, (x, y), \varepsilon|H > h)\mathrm{d}\varepsilon\mathrm{d}m \tag{6}$$

3 Seismic hazard disaggregation for Mainland Portugal

3.1 Re-evaluating seismic hazard

A model of 10 seismogenic zones was considered to re-evaluate seismic hazard for Mainland Portugal. The seismogenic zonation was designed taking into consideration the Portuguese seismotectonic environment (see Fig. 1), but mainly the distribution of historical and instrumental seismicity (with epicentral map shown in Fig. 2) and the principle of adjusting source zones to large geological units. Figure 2 also illustrates the delineated model of seismogenic (or seismic source) zones.

Seismic hazard for Mainland Portugal was re-evaluated following (Frankel 1995) methodology, bearing in mind that seismicity is not uniformly distributed inside source zones, but it is characterized by an empirical density function expressing the spatial distribution of events in the seismic catalogue (see Fig. 3). Only the last century seismicity was used to characterize the referred spatial distribution, in order to take advantage of the more precise location of instrumental epicentres. However, to estimate the remaining parameters that characterize the seismic occurrence process, the historical and instrumental catalogue was considered (Fig. 2). This catalogue covers a time period of approximately 2,000 years and suffered a completeness empirical treatment and an aftershock removal process (Carvalho and Sousa 2001). The complete catalogue, without aftershocks, was used as the base information to estimate the parameters of the Poissonian process and of the exponential distribution of magnitudes for each seismogenic zone (further details may be found in Sousa 1996 or in Sousa and Oliveira 1997).

A summary of the parameters of the occurrence process is shown in Table 1. These are necessary inputs to the PSHA, which assumptions and results are briefly addressed in this section.

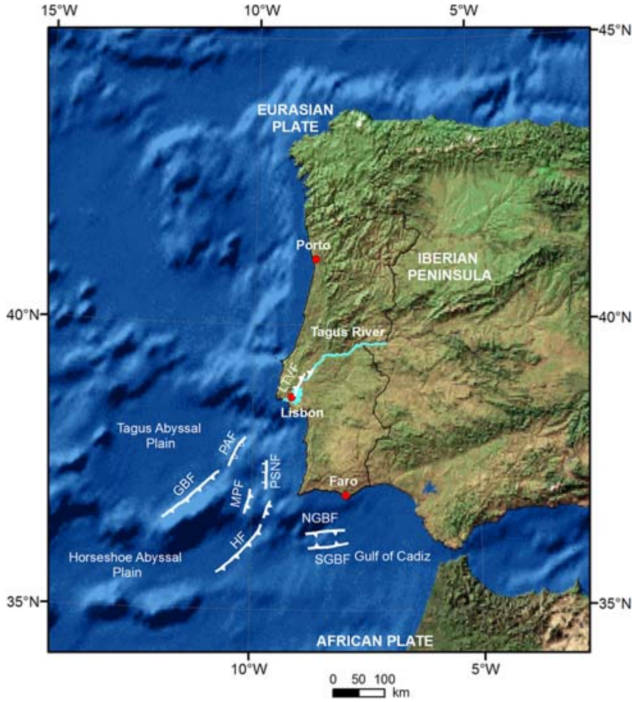

Fig. 1 Western Iberia region and major seismogenic zones in the SW Iberia margin (after Ribeiro 2005 and Ribeiro et al. 2008). GBF—Gorringe Bank Fault; PAF—Príncipes de Avis Fault; MPF—Marquês de Pombal Fault; HF—Horseshoe Fault; NGBF—Northern Guadalquivir Bank Fault; SGBF—Southern Guadalquivir Bank Fault; PSNF—Pereira de Sousa Normal Fault; LTVF—Lower Tagus Valley Fault

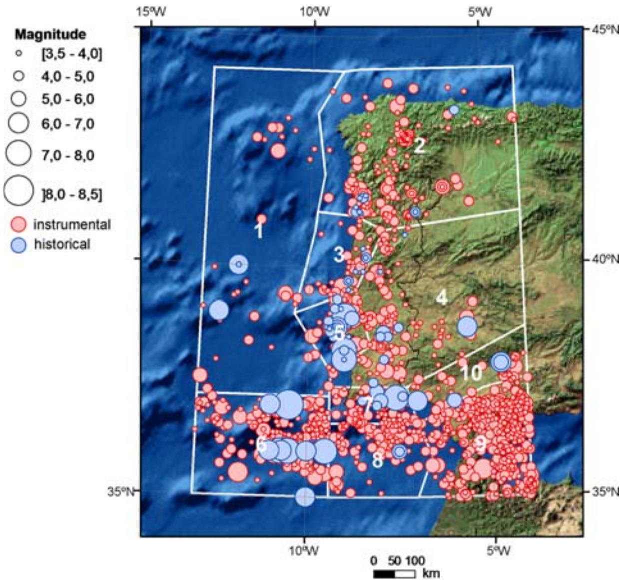

Fig. 2 Epicentral map, 33 AD-1999, M $\geq$ 3.5 (plot using seismic catalogue analyzed by Carvalho and Sousa 2001) and the seismic source zones (adapted from Sousa and Oliveira 1997)

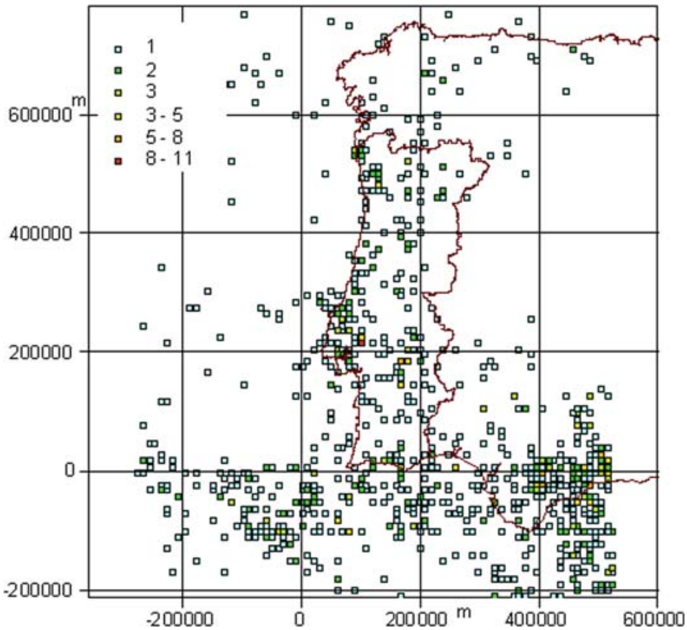

Fig. 3 Number of earthquakes with magnitude greater than 3.5 for each quadratic bin with 10×10 km; instrumental catalogue (year > 1909) without aftershocks

Macroseismic intensity, I, was chosen as the dependent variable in the attenuation models, due to the scarcity of instrumental data in Portugal, mainly for high magnitudes. Five attenuation models, developed by Sousa and Oliveira (1997) for that region, using macroseismic intensity (EMS) as dependent variable were applied:

$$I = c_1 + c_2 \cdot M + c_3 \cdot \ln(R) + c_4 \cdot R + \varepsilon_1 \qquad (7)$$

where c_1, c_2, c_3 and c_4 are the coefficients of a multiple linear regression model that were fitted to the data stored in the Portuguese macroseismic database (Paula and Oliveira 1996) and ε_1 is described as a normal distribution with a null mean and constant variance, $\sigma^2_{\varepsilon_1}$ (Sousa and Oliveira 1997).

Notice that in this simplified model, where $\sigma^2_{\varepsilon_1}$ is assumed statistically independent of M and R, ε_1 is a direct measure of the deviation of ground motion from the predicted motion (median).

Table 1 Maximum magnitude ($m_{\max}$) and estimates of b value of Gutenberg-Richter law for each source zone k (Sousa 2006)

Source zone	$m_{\max k}$	b_k	Source zone	$m_{\max k}$	b_k
1	7.0	−0.66	6	8.5	−0.59
2	6.0	−0.84	7	7.8	−0.92
3	5.6	−0.89	8	7.1	−0.64
4	7.0	−0.84	9	6.2	−1.22
5	7.2	−0.95	10	7.0	−0.87

This is a different approach from standard disaggregation studies, where the error term is usually separated into two parts: $\varepsilon \cdot \sigma$ (Bazzurro and Cornell 1999). The first part, ε, is a measure of the number of standard deviations, σ, that the ground motion Y deviates from the mean μ (USGS 2005):

$$\varepsilon = \frac{y - \mu}{\sigma} \tag{8}$$

where the ground motion Y is modelled as a lognormal variate, $y = \ln(Y)$, and ε is statistically independent of M and R.

Regarding the development of the attenuation models, it is recognized that the above mentioned Portuguese macroseismic database stores macroseismic information of 199 earthquakes felt in Mainland Portugal, with known epicentre. Among those 199 earthquakes, the greatest number (194) occurred between 1947 and 1993 and the remaining are large historical events (Sousa and Oliveira 1997).

Several attempts were made to fit Eq. 7 to macroseismic data stored in the database. As a first approach, Sousa and Oliveira (1997) tried to fit a single attenuation model to each source zone. However, macroseismic data in each zone neither supported a valid statistical analysis, nor guaranteed that the attenuation models have reasonable magnitude application domain for hazard analysis. In fact, the database covers a more limited range of magnitudes than the catalogue, as a consequence of its lesser time span. Therefore, five subsets of the available macroseismic data, resulting form grouping some seismic sources zones, were used to obtain regional attenuation models. In what concerns source zones 5, 6 and 8, macroseismic data was adequate to derive specific attenuation models for each of these zones. A fourth additional model used data from earthquakes located in a group of offshore source zones (1, 6, 8) and a fifth attenuation model used data from earthquakes located in a group of onshore source zones (2, 3, 4, 5, 7 and 10, see Fig. 2 and Sousa and Oliveira 1997).

A final remark regarding the macroseismic intensity quantity: even though it is defined as a discrete ordinal variable, it is assumed in this paper, for statistical analysis, that macroseismic 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 modelling was performed with these variables (Sousa and Oliveira 1997).

Figure 4 exhibits the results of PSHA for Mainland Portugal and for three probabilities of exceedance (PE), PE = 10% in 10 years, PE = 10% in 50 years and PE = 5% in 50 years, corresponding to the 95, 475 and 975 years return periods, respectively. This figure also identifies three important Portuguese cities (Porto, Lisbon and Faro) where disaggregation analysis will be graphically illustrated, although it has been carried out for the all 278 counties of the region. For the same return period these cities are representative of different hazard severity levels in Portugal.

Figure 5 shows seismic hazard curves for the three above mentioned sites. In practice, the integrations in the PSHA (expression 1) where performed numerically and the elementary annual frequency of exceedance where assigned to the central point of each bin, with constant dimensions in the domain of analysis: $\Delta m = 0.1$, $\Delta x = \Delta y = 10\,\text{km}$ and $\Delta\varepsilon_1 = 0.25$.

3.2 Univariate disaggregation of and of ε_1

Figures 6 and 7 exhibit the 1D disaggregation analysis of the random variables M and ε_1, respectively, regarding Porto, Lisbon and Faro counties, conditioned by the hazard levels correspondent to the probabilities of exceedance referred in Fig. 4. Mean, $\bar{M}$ and $\bar{\varepsilon}_1$, and

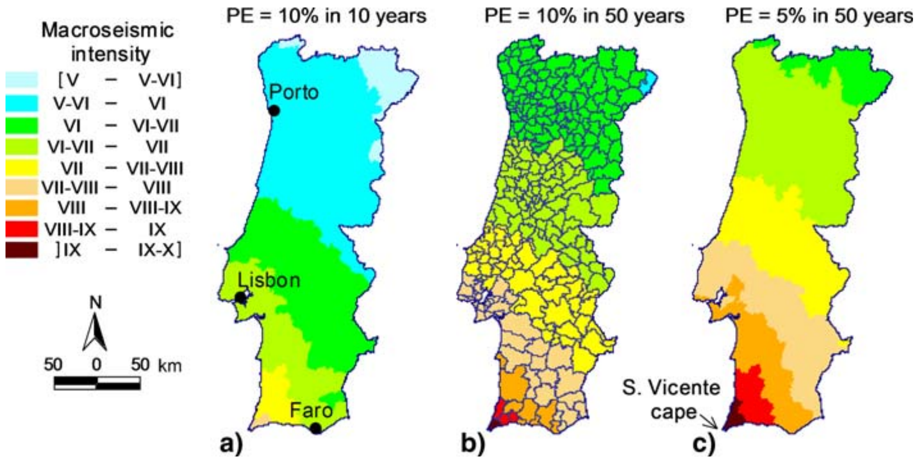

Fig. 4 Seismic hazard maps for Mainland Portugal; probabilities of exceedance (PE) of 10% in 10 years, 10% in 50 years and 5% in 50 years. Map (**a**) also represents the three sites where hazard disaggregation is analyzed in more detail, whereas map (**b**) shows the 278 Portuguese counties and map (**c**) the South-Western point of Mainland Portugal

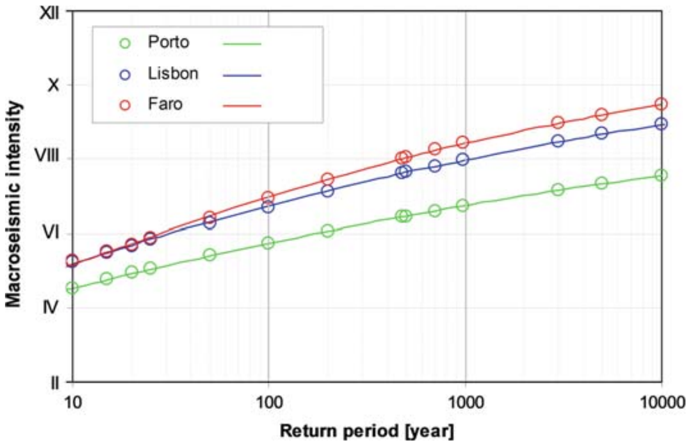

Fig. 5 Seismic hazard curves for three cities in Mainland Portugal. Solid lines represent the best fit obtained to hazard curves that were originally computed for 14 return periods

modal, $\hat{M}$ and $\hat{\varepsilon}_1$, values of the probability marginal distributions of the random variables M and ε_1, may also be found in those figures.

From the analysis of Fig. 6 it can be noted that:

1. The marginal magnitude distributions show an upper bound at 8.5, corresponding to the highest magnitude upper limit of Gutenberg-Richter models estimated for the region (see Table 1).
2. Mean, $\bar{M}$, and modal, $\hat{M}$, values of the conditional marginal magnitude distribution increase as return period does. The only exception is the modal value concerning Porto county, for the 975 years return period, which is similar to the modal value associated to the 475 years return period. This limitation on the modal value growth results from the referred bounded Gutenberg-Richter distribution of magnitude with a maximum upper limit of 8.5.

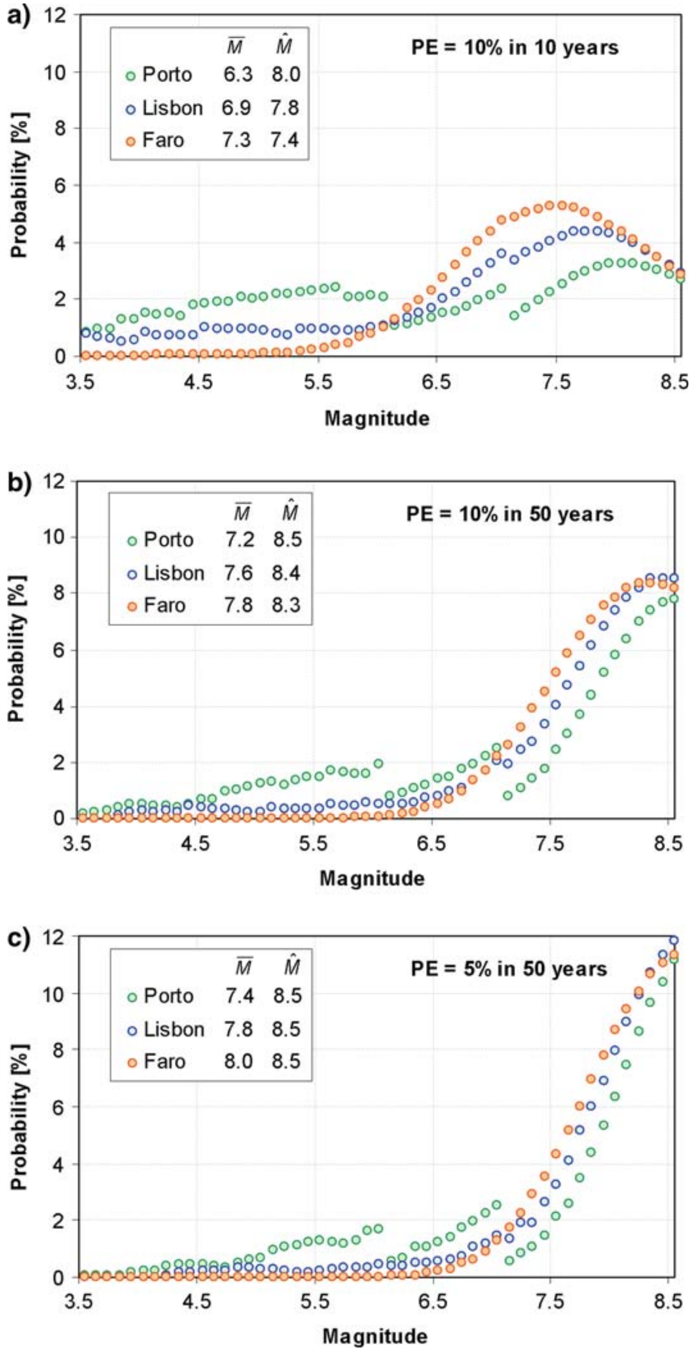

Fig. 6 Seismic hazard disaggregation of the random variable M, for Porto, Lisbon and Faro counties and for three return periods: (**a**) 95, (**b**) 475 and (**c**) 975 years. Also shown are mean and modal values of M

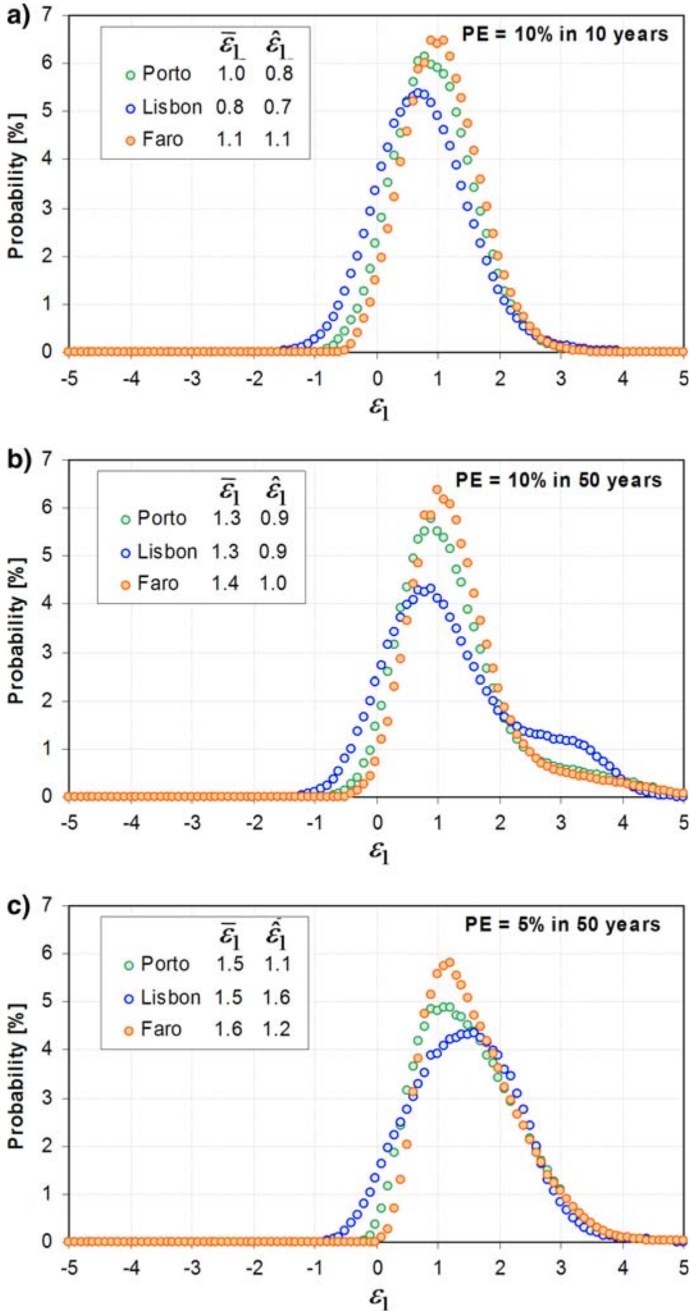

Fig. 7 Seismic hazard disaggregation of the random variable ε_1, for Porto, Lisbon and Faro counties and for three return periods: (**a**) 95, (**b**) 475 and (**c**) 975 years. Also shown are mean and modal values of ε_1

3. Regarding Porto county, and for the three return periods analyzed, the probability marginal distribution of magnitude reveals a multi-modal pattern, with some discontinuities, coincident with the magnitude upper bound of the seismic source zone that contributes to the hazard of that site. This reveals that seismic source zones affecting a site are multiple, justifying, as Montilla (2000) supports, the existence of significant differences between magnitude mean and modal values. Cleary, the right most segment of the probability marginal distribution of magnitude is controlled by the seismic source zone no. 6, because this is the only one with such a high magnitude upper bound (see Table 1). Similar pattern may be found in the marginal magnitude distribution for Lisbon county, conditioned by a hazard level with an exceedance probability of 10% in 10 years. This distribution shows a secondary mode between magnitudes 6.5 and 7.5, reflecting that a second source zone is responsible for a lesser contribution to this county hazard level.
4. In what concerns the geographic variation of the central statistics (means and modes) one verifies that magnitude mean values always increase from Porto to Faro (North to South), assuming an intermediate value in Lisbon county. The inverse situation occurs when magnitude modal values are analyzed, mainly in the lowest analyzed return period (95 years). As a tentative explanation of means and modes opposite behaviour, one may say that mean magnitude increases from North to South, reflecting the geographic increase of hazard severity for the same return period. On the other hand, the decrease of modal magnitude from North to South is better understood when the random variable distance is also considered in the disaggregation analysis (Sects. 3.4 and 3.5). In that case, we may observe that the distant location between the controlling zone no. 6 and Northern counties is balanced by an increase of the modal magnitude for those counties. This behaviour is more evident in the lowest analyzed return period (95 years), because, in the higher ones, the magnitude modal values are close to the highest magnitude upper bound of the controlling seismic source zone.

Analyzing Fig. 7 one may conclude that:

1. Conditional marginal ε_1 distributions are, generally, unimodal, except for Lisbon county and for a exceedance probability of 10% in 50 years, where the distribution shows a bi-modal pattern, revealing the existence of a secondary hazard scenario with a ε_1 value around three degrees of macroseismic intensity.
2. Mean and modal values of the marginal ε_1 distribution, conditional on the exceedance of the intensity level i, are always greater than zero, varying around the unitary value of intensity. This means that most dominant shaking scenarios exceed, in more than one macroseismic intensity degree, the median value predicted by the attenuation model.
3. Mean and modal values of the conditional marginal deviate distribution, $\bar{\varepsilon}_1$ and $\hat{\varepsilon}_1$, increase as return period does.

3.3 Geographic hazard disaggregation of (X, Y)

This section addresses seismic hazard geographic disaggregation analysis (2D) evaluating the marginal joint distribution of random variables (X, Y) (expression 6). In practice, this evaluation corresponds to numerically accumulate in each bin all the elementary contributions Δm and $\Delta\varepsilon_1$. Table 2 put together the modal values identified by the 2D hazard geographic disaggregation for the three analyzed cities and for the three hazard levels. The maximum relative contribution to the exceedance of the hazard level is identified as the 1st mode. When there is a second relative contribution to hazard with a similar importance as the first mode,

Table 2 Modal values obtained by geographic disaggregation for return periods (RP) of 95, 475 and 975 years (different colours); also shown the proportion of total hazard caused by modal pairs $\hat{X}$, $\hat{Y}$ (labelled "contrib."), the distance of modal bins to the site and the average values of M and ε_1, conditional on modal cells $(\hat{X}, \hat{Y})$ and on the exceedance of the hazard target levels, i

	RP [year]	mode	contrib. [‰]	$(\hat{X},\hat{Y})$ [km]	$\hat{R}$ [km]	$\overline{M}$ |[$(\hat{X},\hat{Y}), I>i$]	$\overline{\varepsilon}_1$ |[$(\hat{X},\hat{Y}), I>i$]
Porto	95	1st	56.5	176.3; 481.2	23.8	4.8	1.83
	475	1st	37.9	176.3; 481.2	23.8	5.1	2.29
		2nd	22.0	67.3; -4.4	477.9	7.9	1.00
	975	1st	27.1	67.3; -4.4	477.9	8.0	1.13
		2nd	25.4	176.3; 481.2	23.8	5.2	2.47
Lisbon	95	1st	34.7	67.3; -4.4	204.7	7.2	0.67
		2nd	28.9	146.5; 213.6	38.3	5.1	2.63
	475	1st	52.9	67.3; -4.4	204.7	7.7	0.82
	975	1st	64.0	67.3; -4.4	204.7	7.8	0.94
Faro	95	1st	52.8	67.3; -4.4	150.8	7.0	0.66
	475	1st	69.8	67.3; -4.4	150.8	7.6	0.77
	975	1st	76.5	67.3; -4.4	150.8	7.8	0.82

it is referred as the 2nd mode. Table 2 also shows the amplitude of $\hat{\mathbf{R}}$ that defines the distance between the modal geographic location $(\hat{X}, \hat{Y})$ and the site under analysis. In addition, Table 2 presents the mean values of M and ε_1 conditional on the modal cells and on the exceedance of the hazard target levels.

Figure 8 illustrates the geographic disaggregation analysis (2D) for Porto, Lisbon and Faro, conditional on the exceedance of the 475 years return period hazard level. In this figure, bar height represents the relative contribution of each bin (X, Y) to the exceedance of the hazard target levels, i, in each site. Figure 8 also shows the mean magnitude, for each cell, conditional on the referred 475 years return period.

3.4 Bivariate hazard disaggregation of M and R

Figure 9 illustrates 2D hazard disaggregation of M and R. The same figure incorporates bivariate mean and modal values of M and R for the three above mentioned sites (Porto, Lisbon and Faro).

The sum of all contribution to hazard levels shown in this figure should be equal to $1000^0/_{00}$. However, in order to simplify plotting, contributions lesser than $0.1^0/_{00}$ were disregarded. Notice that all graphics share the same vertical scale, allowing a more detailed analysis for lower return periods.

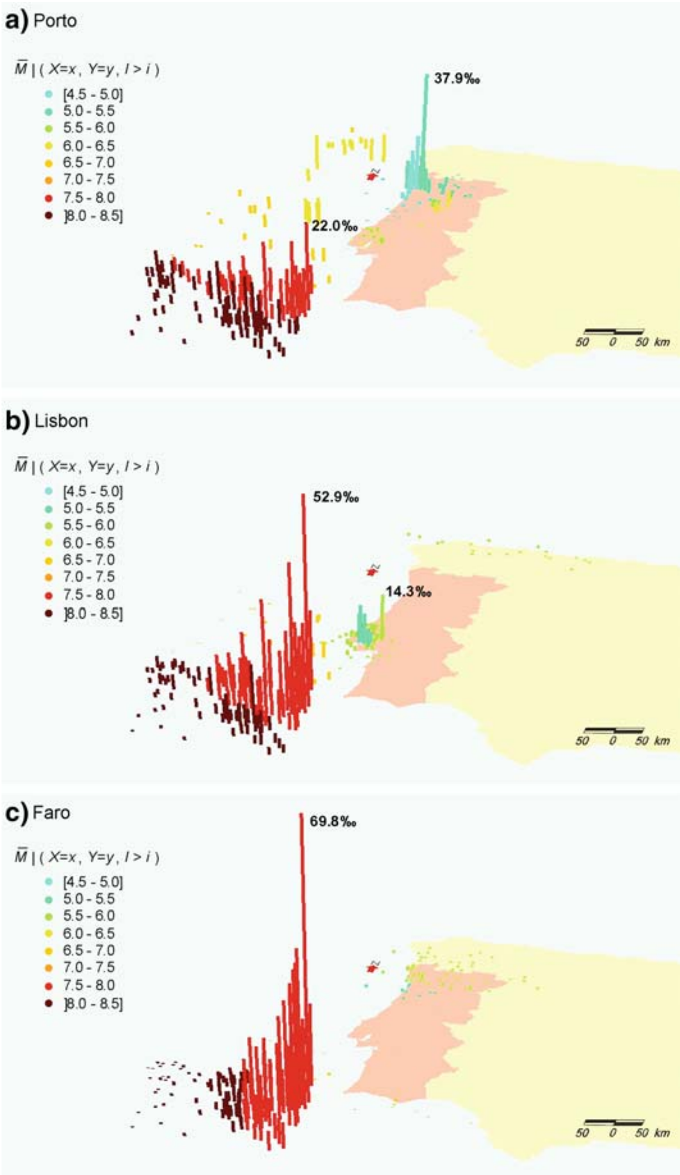

Fig. 8 Geographic seismic hazard disaggregation conditional on the exceedance of the seismic hazard level for the 475 years return period, illustrated for 3 Portuguese cities: (**a**) Porto, (**b**) Lisbon and (**c**) Faro. Also shown: (i) the average magnitude for each cell and (ii) the contribution to each site hazard level of dominant and secondary scenarios

The following conclusions were obtained from the analysis of this bivariate disaggregation:

1. Regarding Porto site, and till the 475 years return period, the bivariate mode of the marginal distribution in the geographic space $(\hat{X}, \hat{Y})$ was located in the proximity of this county, (see Table 2 and Fig. 8a). When the random variable magnitude was also considered in hazard disaggregation (Fig. 9a–c), the bivariate mode, conditioned by the hazard

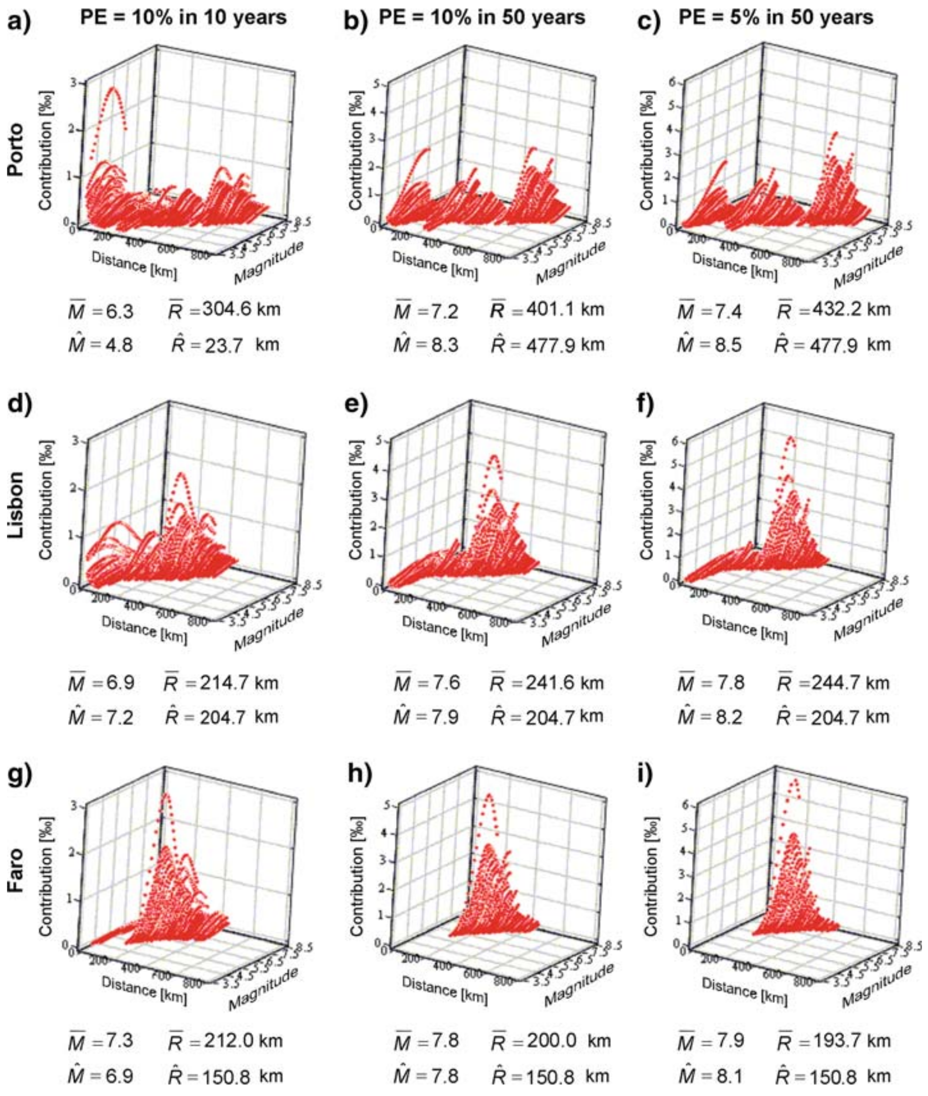

Fig. 9 Joint probability distribution of magnitude and distance for 95, 475 and 975 years return periods, for Porto, Lisbon and Faro counties

level of 475 years return period, is shifted to a distant cell and, consequently, the modal magnitude of the joint distribution increases. Figure 9a–c evidences that several sources are relevant to the exceedance of Porto ground motion levels. In fact, just like in Fig. 6, this distribution shows a multi-modal pattern and their discontinuities reveal that hazard dominant scenarios are multiple.

2. In what concerns Lisbon county, Fig. 9d–f also shows a multi-modal characteristic of 2D disaggregation of M and R; this kind of pattern is more evident in the 95 years return period (Fig. 9d). In Lisbon, the 2D disaggregation of M and R confirms that modal

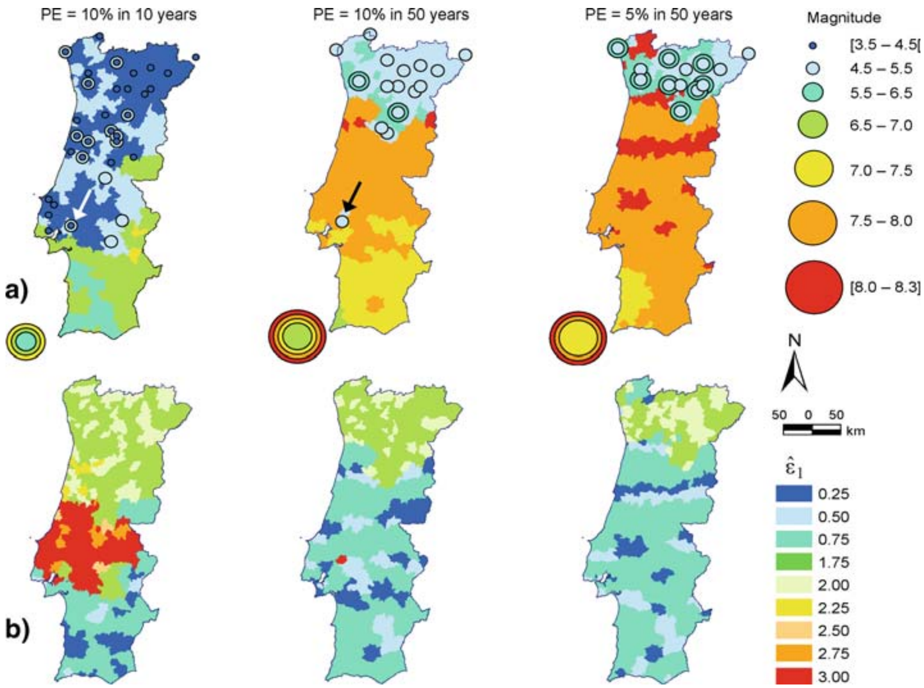

Fig. 10 Seismic hazard dominant scenarios by county: (**a**) scenarios location and magnitude; (**b**) maps of deviates by county

scenarios are distant, that was a result already pointed out by the geographic disaggregation (Fig. 8b).

3. The 2D disaggregation of M and R for Faro county (Fig. 9g–i) also confirms that modal scenarios are distant, that was a result also pointed out by the geographic disaggregation (Fig. 8c). This figure also indicates that the exceedance of all hazard levels is dominated by the same source zone.
4. Figure 9 shows that M mean values of the bivariate disaggregation of M and$R$ are very close to the mean values of the marginal magnitude distribution shown in Fig. 6.

3.5 4D disaggregation of M–(X, Y)–ε_1

For each of the 278 counties of Mainland Portugal the results of a 4D seismic hazard disaggregation analysis is summarized in one measure of position: the mode of the joint probability distribution of the variables M–(X, Y)–ε_1, conditional on the exceedance of a hazard level i at the site.

The three maps in the upper part of Fig. 10 present, for the return periods of 95, 475 and 975 years, the location and magnitude of the so identified 278 modal scenarios. Circle location coincides with each county scenario epicentre, whereas circle colour, or its dimension, makes reference to the scenario magnitude. In Fig. 10a, each county is plotted with the same colour of its scenario magnitude. The three maps shown in Fig. 10b present the values of deviates ε_1 for each county return period.

Figure 10 has the advantage to gather, in a compact way, the 4D disaggregation modal scenarios for the 278 Portuguese counties and for 3 return periods. This figure allows a

Table 3 Seismic hazard scenarios obtained by 4D disaggregation analysis; exceedance probability of 10% in 10 years, 10% in 50 years and 5% in 50 years

	RP [year]	Mode	contrib. [‰]	$(\hat{X}, \hat{Y})$ [km]	$\hat{R}$ [km]	$\hat{M}$	$\hat{\varepsilon}_1$
Porto	95	1st	1.74	176.3; 481.2	23.8	4.5	1.75
	475	1st	1.53	176.3; 481.2	23.8	5.4	1.75
		2nd	0.70	67.3; -4.4	477.9	7.8	0.75
	975	1st	1.44	176.3; 481.2	23.8	5.8	1.75
		2nd	1.10	67.3; -4.4	477.9	8.0	0.75
Lisbon	95	1st	0.70	146.5; 213.6	38.3	4.5	3.00
		2nd	0.63	67.3; -4.4	204.7	6.7	0.75
	475	1st	1.21	67.3; -4.4	204.7	7.4	0.75
	975	1st	1.89	67.3; -4.4	204.7	7.8	0.50
Faro	95	1st	0.94	67.3; -4.4	150.8	6.4	0.75
	475	1st	1.59	67.3; -4.4	150.8	7.2	0.75
	975	1st	2.17	67.3; -4.4	150.8	7.5	0.75

global understanding of their geographic variation and of the influence of return periods. Nevertheless, this figure doesn't permit to associate, unequivocally, some counties with the magnitude and location of their modal scenarios, namely the inland located lower magnitude ones. To reduce this disadvantage, Table 3 makes explicit the modal scenarios (1st mode) for Porto, Lisbon and Faro, for the above mentioned return periods, and their relative contribution to the hazard of the site. Secondary scenarios (2nd mode) are also identified in Table 3, when, for a specific return period, it is detected a second relative contribution to hazard with a similar importance as the first mode, but with a distinct geographic location (just like in Table 2 and in Fig. 8).

3.6 Analysis of hazard dominant scenarios

Results of 4D disaggregation analysis, presented in Table 3, pointed out the existence of two geographic relevant modes to Porto county, for the 475 and 975 years return periods, and to Lisbon county for the 95 years return period. In Faro, hazard disaggregation reveals a unimodal pattern for the analyzed return periods.

The majority of the 278 analyzed counties, mainly in what concerns high return periods, share an offshore scenario located at 70 km WSW of S. Vicente cape (the South-Western point of Iberian Peninsula that is identified in Fig. 4), representing a larger or smaller contribution for their seismic hazard level.

The hazard of Northern counties is predominantly dominated by nearby scenarios, whereas the offshore scenario above mentioned is responsible for a secondary contribution. Such a bimodal pattern is also revealed in central counties, but only for low return periods. The

Southern Portuguese counties show a unimodal distant dominant scenario, similar to the results obtained in Faro.

It must be noticed that this pattern of dominant scenarios has already appeared in the 2D geographic disaggregation shown in Fig. 8. So one may conclude that, for the three exemplificative sites and return periods, the 2D geographic disaggregation is a good indicator of the location where to perform 4D seismic hazard disaggregation analyses, which requires higher computational efforts. In what concerns the referred exemplificative cases, the mean magnitudes and deviates, conditional on modal cells and on the exceedance of the hazard target levels (Table 2), are similar to the magnitudes and deviates of the corresponding 4D scenarios (Table 3). Comparing those two tables only two interchanges of the first mode with the secondary one were identified. These are the cases of Porto, for 975 years return period, and of Lisbon, for 95 years return period.

Analyzing the relation between the dominant offshore scenario located at 70 km WSW of S. Vicente cape and the past seismicity, one may advance that this scenario is located in the North-Eastern part of seismic source zone no. 6 (see Fig. 2), that is a geographically extensive zone where the 1755 earthquake location was considered. This emblematic event has the highest estimated magnitude (8.5–8.7) since historical times in Western Europe (Zitellini et al. 2004). Nevertheless 1755 most probable source rupture is presently under discussion and there are several recent publications addressing this issue that favors different solutions (Baptista et al. 2003; Fonseca 2005; Johnston 1996; Ribeiro 2005; Ribeiro et al. 2008; Terrinha et al. 2003; Thiebot and Gutscher 2006; Vilanova 2004; Vilanova et al. 2003; Zitellini et al. 2001, 2004). Consequently, the seismogenic zonation here adopted may be revised in the future, taking into consideration the most recent advances in this domain.

Based on present assumptions one may conclude that most of the 475 and 975 years return period modal scenarios, over much of the Central and Southern Portuguese counties, are dominated by the effect of the large magnitude 1755 earthquake. The only exception is the 475 years return period modal scenario for Salvaterra de Magos county, identified by a light blue circle located in lower Tagus valley (see indicative black arrow in Fig. 10a, middle), that reflects the influence of 1531 and 1909 Benavente earthquakes with epicentre in this region.

3.7 Reproducing hazard target values with dominant 4D disaggregation scenarios

Finally, each county dominant scenario, obtained by 4D seismic hazard disaggregation, was substituted in an attenuation model in order to investigate how close it reproduces the hazard target values. More precisely, for each return period, the triplet $(\hat{M}, \hat{R}, \hat{\varepsilon}_1)$ of values correspondent to (i) the joint modal magnitude, (ii) the distance between joint modal bin $(\hat{X}, \hat{Y})$ and the analyzed county and (iii) the joint modal deviation, $\hat{\varepsilon}_1$, were substituted in the ground motion attenuation relationship (expression 7), with coefficients appropriated to the source zone in which the county dominant scenario is located.

The experience of Bazzurro and Cornell (1999) in this matter allows them to say that the values predicted by attenuation models using modal scenarios usually exceed target hazard values within 20%. In this work, we remark that the substitution of modal values $\hat{M}$–$\hat{R}$–$\hat{\varepsilon}_1$ in the proper attenuation model results on a prediction of intensity values with a very small exceedance difference from the hazard target level for the site. In fact, among the 278 Mainland Portuguese counties and the 14 hazard return periods for which disaggregation was analyzed, the mentioned differences vary between 0.0001 and 2.77%, with an average value of 0.58% and a standard deviation of 0.45%. It was also verified that attenuation models, applied to modal values, always predict ground motions in excess relatively to the hazard target values.

In what concerns the three exemplificative return periods shown in Fig. 10 (95, 475 and 975 years), the relative differences between the hazard target levels and the attenuation model predictions are even smaller, attaining a maximum value of 1.56%.

Regarding 4D seismic disaggregation analysis one may conclude that seismic movements predicted by the attenuation models, when applied to the 278 scenarios that dominate the hazard in each Portuguese county, reproduce quite well each site hazard target level presented in Fig. 4. Examples of possible applications of this result are addressed in the final chapter.

4 Conclusions and future work

Results of the present study were compared to Montilla (2000) and Montilla et al. (2002) studies that performed 2D disaggregation analysis in M–R and 3D disaggregation analysis in M–R and azimuth, for some cities in Mainland Portugal. The main differences are that, in Montilla studies, hazard is mainly dominated by nearby scenarios. These discrepancies may be justified by the differences in the used catalogue and attenuation models.

In fact, the results obtained are highly dependent on the geographic distribution of seismicity and on the attenuation relations, emphasizing the relevance of sensitivity studies concerning seismic catalogues and attenuation models.

The main objective of the present work was achieved, as it was possible, via an objective criterion, to choose seismic scenarios that dominate some hazard levels of Mainland Portuguese counties. As a result, and referring (McGuire 1995), we are "closing the loop" between probabilistic seismic hazard analysis and the identification of scenarios that predict the seismic threat to a site, conditioned by the exceedance of a specific probability.

The most important conclusions derived from the obtained results are the following:

1. Hazard scenarios obtained by geographic hazard disaggregation, in (X–Y) revealed to be an excellent indicator of the location of scenarios obtained by disaggregation of M–(X–Y)–ε_1, saving computational efforts. This evidence was verified for the three exemplificative sites and return periods.
2. The lower the return period the higher is the number of modal scenarios with epicentre in the proximity of the analyzed site and the higher is the amplitude of the deviates ε_1, as well. For instance, in what concerns the 95 years return period, 21% of Portuguese Mainland counties share the same dominant scenario located in the Lower Tagus Valley (see indicative white arrow in Fig. 10a left).
3. Seismic hazard of most Portuguese Mainland counties is dominated by the seismicity located offshore, at South-West of S. Vicente cape, with a higher magnitude scenario as much Northern is the location of the analyzed county. This seismogenic zone is especially relevant for high return periods, gathering the dominant scenarios of 71% of Portuguese counties for the 975 years return period. This conclusion confirms the merit of research efforts presently in course in Portugal regarding 1755 seismogenic zone and suggests that a sensitive analysis on this subject may provide some useful information about the impact of the identified dominant zone in probabilistic hazard estimates (Harmsen et al. 2003).
4. For each return period, hazard modal scenarios may be used to reproduce hazard target values, in each site, with great accuracy. In fact, when modal seismic hazard scenarios, derived from 4D disaggregation studies, are substituted in the attenuation model the obtained ground motion is close to the target conditional hazard level, with a maximum relative error of 2.8%. When short distance dominating scenarios are considered, this

proximity of the soil movement and hazard target value is achieved at the expense of high values of deviates ε_1. This enables the association of an exceedance probability of a hazard level to the applications derived from modal scenarios (e.g. loss evaluation).

This last conclusion opens a wide range of possible applications of these ground motion scenarios consistent with a probabilistic seismic hazard disaggregation analysis. For instance, modal scenarios, always associated to a specified return period, may be used (i) to prepare emergency plans for civil protection (ii) to obtain time histories and duration of ground motion to be used as an input to seismic design programs for structural response (Harmsen et al. 2003), (iii) or to model seismic losses for a region.

More specifically, in what concerns the last referred application, one may take advantages of the simplicity of macroseismic models for damage assessment, such as the models proposed by Lagomarsino and Giovinazzi (2006), to carry out a probabilistic loss modelling study (Sousa 2006). These macroseismic models require that ground motion is expressed in terms of macroseismic intensities and, on the contrary of the mechanical models, do not require a considerable computational effort to assess damage. So, disaggregated modal scenarios assessed from PSHA may be used to perform a seismic risk analysis for a region. In fact, risk analysis, with such simplified models will not involve the excessive effort, pointed out by Crowley and Bommer (2006), to compute loss exceedance curves for numerous sites.

Notice however, that at the same time this paper is being submitted, new earthquake ground-motions attenuation relations developed for Portuguese seismotectonic environment are being published (Carvalho 2007). Those relations are based on a finite fault non-stationary stochastic seismological model and are the first spectral attenuation laws derived specifically for this region. In consequence, in the near future, seismic hazard will, most probably, be re-evaluated, with the advantage of the disaggregation tool being operational.

On the other hand, it is worth to mention that a spectral description of modal scenarios will most likely not originate such a compact result, like the one obtained in this study. In fact, the results here presented comprise a small number of different controlling scenarios for the region, as they were derived from an analysis based on a unique ground motion intensity measure.

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