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ASSESSMENT OF UNIFORM DISPLACEMENT SPECTRA BY PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA): APPLICATION TO LISBON 1ST YEAR REPORT

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NODISASTR – Novel use of displacement-based design for seismic assessment and strengthening of RC buildings

PROJECT ENVIRONMENT ENV4

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C3ES

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NODISASTR 1st year progress report

Activity at the National Laboratory for Civil Engineering (LNEC)

Assessment of Uniform Displacement Spectra by Probabilistic Seismic Hazard Analysis (PSHA): Application to Lisbon

1. INTRODUCTION

The present progress report describes the research developed by LNEC under the ENVIRONMENT project ENV4-CT97-0548, entitled "Novel use of displacement-base design for seismic assessment and strengthening of RC buildings (NODISASTR)", during its first year of activity and referring to tasks *4.1 Seismic Hazard for Spectral Displacements* and to a special application to the region of Lisbon.

In what concerns task 4.1 it was defined the methodology, based in probabilistic tools, to incorporate frequency-dependent attenuation relationships in seismic hazard analysis in order to estimate an *Uniform Risk Spectra* (URS) associated to a given return period (chapter 2). The spectral ordinates of a URS have the same probability of being exceeded during the life time of the facility due to the seismicity of the sources affecting the site.

To accomplish the project goals the frequency-dependent attenuation relationships used to estimate an URS must be expressed in displacement spectral ordinates for various discrete values of period or frequency, and must be adequate to Europe. In the scope of the present project it become recently available frequency (period) dependent attenuation relationships where the predicted strong motion parameter are displacement spectral ordinates [Borzi, *et al.*, 1998].

The project benefited from the results achieved in another ENVIRONMENT project, entitled "Theoretical Research in Earthquake Prediction and Identification of Zones of Seismic Potential" (EV5V - CT94/0443), namely in what concerns the characterisation of the seismic process of occurrence in Portugal [Oliveira & Sousa,1999] (summary in chapter 3).

The above mentioned methodology was implemented in the computer algorithms based on the standard Cornell/McGuire approach, that were upgraded to estimate an URS associated to a given return period.

The developed methodology and the computer procedures were applied to a specific case study representing the first step in the progress of task 5. It was chosen the city of Lisbon to assess the probabilistic seismic hazard in terms of uniform displacement spectra (chapter 4).

2. SEISMIC HAZARD ANALYSIS: A PROBABILISTIC METHODOLOGY

2.1 Mathematical background

The purpose of the PSHA is to obtain the probabilistic descriptions of seismic motion intensities at a particular site, due to possible ruptures taking place on the seismotectonic structures that contribute to the seismicity of the site. More precisely, the goal of the PSHA is to evaluate the probability of exceeding a given seismic intensity level of ground motion *y*, at a given site, knowing that an earthquake occurred in any point of a set of seismic sources zones (modelled as arial or linear zones). This is schematically depicted in figure 2.1, where different sources contribute to the seismicity of a given site, located itself inside a seismic source zone.

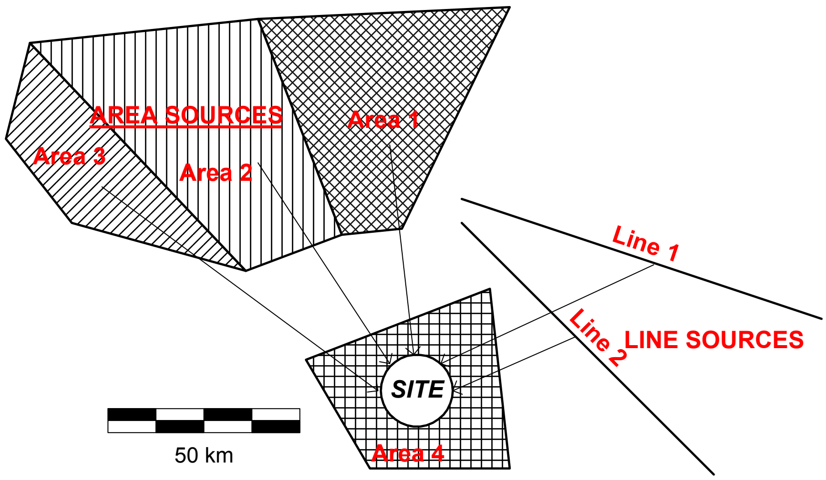

Figure 2.1 - Schematic representation of the Probabilistic Seismic Hazard Analysis.

The following main topics are involved in a PSHA:

1. Probabilistic modelling of earthquake occurrences in space and time including the geometric descriptions of the potential seismic sources (e.g. faults). For each seismic source zone it must be assessed the activity rate for earthquakes with magnitude greater than a given lower value *m0*, and estimated the maximum capacity of energy release expressed by the maximum probable magnitude value *mu*.
2. Description of a recurrence relationship, for each seismic source zone, providing the relative frequency of occurrence of earthquakes of different magnitudes between the limits *m0* and *mu*.

3. Description of the attenuation of ground motion with distance from each seismic source to a specific site, taking into account path effects on the travelling waves and the local soil dynamic behaviour.

Each of the above topics involves uncertainties. The theoretical background of PSHA was developed by Cornell [Cornell, 1968, 1971; Merz and Cornell, 1973], and includes the modelling of those uncertainties through probabilistic methods.

From a mathematical point of view the PSHA can be formulated as follows: let the site seismic intensity *Y* be a random variable dependent on a set of random variables given in the vector **x**. The probability $P(Y>y)$ that the site seismic intensity does exceed a certain level *y* can be computed applying the Total Probability Theorem, expressed as:

$$P(Y > y) = \int P(Y > y|\mathbf{x}) \cdot f_{\mathbf{x}}(\mathbf{x}) \cdot d\mathbf{x} \tag{2.1}$$

where $P(Y>y|\mathbf{x})$ indicates the conditional probability of occurring an intensity greater than a certain level *y*, given that a sample vector **x** had occurred; $f_{\mathbf{x}}(\mathbf{x})$ is the joint probability density function of the random variables **x**.

If one considers that the site seismic intensity is reasonable described by *n* uncorrelated variables $x_1, x_2 \ldots x_n$ the integral equation 2.1 can be simplified to:

$$P(Y > y) = \int\int \cdots \int P(Y > y|x_1, x_2, \cdots, x_n) \cdot f_1(x_1) \cdot f_2(x_2) \cdots f_n(x_n) \cdot dx_1 \cdot dx_2 \cdots dx_n \tag{2.2}$$

Uncertainties in the quantification of seismic intensity at a given site are caused by (i) the randomness of the variables related to the amount of energy released, (ii) the randomness of the epicentral location in each source zone and (iii) by the uncertainties in the variables associated to the physical phenomena of propagation and attenuation of that energy from the source to the site.

Typically in PSHA uncertainties are modelled by (i) the probability distribution of the magnitude *m*, (ii) the probability distribution of the location of events within each idealised source zone (that location can be transformed to a random variable distance *R* from the source to the site) and (iii) by the random functional descriptions known as attenuation laws.

Furthermore, as generally assumed, the random variables magnitude *M* and epicentral distance *R* are statistically independent. Then the computation of $P(Y>y)_i$, taking into account each seismic source *i* separately, is given by:

$$P(Y > y)_i = \int_R \int_{mo_i}^{mu_i} P(Y > y|m, R) \cdot f_M(m)_i \cdot f_R(R)_i \cdot dm \cdot dR \tag{2.3}$$

in this particular case $P(Y>y|m,R)$ gives the conditional probability of exceeding the intensity level y at a site, given that an earthquake of magnitude m and distance R has occurred in a seismic source zone i; $f_M(m)_i$ represents the probability density function (*pdf*) associated to the likelihood of the magnitude of events ($m0_i<m<mu_i$) occurring in zone i and, $f_R(R)_i$ represents the *pdf* used to reflect the randomness of epicentral location of earthquakes inside each source i.

If, as usually, $f_R(R)_i$ is assumed uniformly distributed, expression 2.3 becomes:

$$P(Y > y)_i = \int_R \int_{mo_i}^{mu_i} P(Y > y|m, R) \cdot f_M(m)_i \cdot dm \cdot dR \tag{2.4}$$

On the other hand, if instead of an unique ground motion parameter intensity Y, PSHA is performed for some spectral description of site intensity, and the values of spectral ordinates are uncorrelated, expression 2.4 can be generalised for the j ordinate in the form:

$$P(S_j > s_j)_i = \int_R \int_{mo_i}^{mu_i} P(S_j > s_j|m, R) \cdot f_M(m)_i \cdot dm \cdot dR \tag{2.5}$$

where $P(S_j > s_j|m,R)$ gives the conditional probability of exceeding, at the site, the spectral ordinate s_j, at a frequency (or period) f_j, given that an earthquake of magnitude m has occurred at a distance R in the seismic source zone i.

Spectral ordinates of a PSHA constitute, what is generally called, the Uniform Risk Spectra, URSs. As mentioned before those spectral ordinates have the same probability of being exceeded, in a given exposure period of time, due to the seismicity of the seismic source i.

In PSHA the procedures for estimating the values *m0*, *mu* and other parameters associated to $f_m(m)$ are generally called modelling earthquake *magnitude recurrence*, whereas the idealisation of attenuation relationships and the associated estimates of $P(Y>y|m,R)$ are referred as modelling the *attenuation of seismic intensity*. The next two sections will be devoted to those topics.

2.2 Earthquake magnitude recurrence models

As already mentioned seismic sources must be physically characterised in terms of their seismotectonic potential for releasing energy. In other words the issue of this important aspect of PSHA is to establish a law that describes the relative frequency of earthquakes with magnitudes greater than a lower limit *m0*, in a given region, and in a specified period of time.

In general, those laws are empirically deduced taking into account all magnitudes greater than *m0*, of the earthquakes with epicentral location inside each zone. That task is carried out by the statistical analysis of earthquake catalogues for the region of interest (containing all seismic source zones). Furthermore, only a given time window of the available catalogues are taken into account, in order to assure their completeness; this implies that the property of stationary is assumed for the recurrence magnitude models.

According to Araya & Kiureghian [1988] the first attempts to model the earthquake magnitude recurrence where made by Ishimoto & Iida [1939] and by Gutenberg & Richter [1944], who independently proposed a linear relation between the logarithm (decimal) of the frequency and the magnitude. This model is currently known as the Gutenberg-Richter law:

$$\log N(m) = a - b \cdot m \qquad \text{or} \qquad N(m) = \exp(\alpha - \beta \cdot m) \tag{2.6}$$

where $N(m)$ represents the number of earthquakes with magnitude greater than or equal to m, in a given region, and specified period of time, and $\alpha=2.3a$ and $\beta=2.3b$ are the parameters to be fitted to the catalogue data.

If events with magnitude less or equal to *m0* are assumed to have no engineering importance, and if it is recognised the existence of a regional maximum probable magnitude *mu*, then the cumulative distribution of magnitudes of the earthquakes with epicentres inside source i is easily derived as:

$$F_M(m)_i = P(M < m | m0 \leq M \leq mu)_i = \frac{N(m0)_i - N(m)}{N(mu)_i - N(m0)_i} = \frac{1 - e^{-\beta_i \cdot (m - m0_i)}}{1 - e^{-\beta_i \cdot (mu_i - m0_i)}} \tag{2.7}$$

By differentiating the last expression the correspondent probability density function can be obtained:

$$f_M(m)_i = \frac{\beta_i \cdot e^{-\beta_i \cdot (m - m0_i)}}{1 - e^{-\beta_i \cdot (mu_i - m0_i)}} \tag{2.8}$$

Other recurrence magnitude models have been used in PSHA such as the bilinear law used by the group of Stanford University researchers [Shah *et al.*, 1975] and the quadratic law introduced by Merz & Cornell [1973].

The bilinear law is used to reduce the bias due to incomplete small magnitude data, because, in such cases, a single line overestimates the frequency of large magnitudes and, consequently, the hazards tend to be overestimated [Araya & Kiureghian, 1988].

Also the quadratic law predicts less events of high magnitude than the linear law and its use in the PSHA is significant for high intensity levels, with hazard curve falling off faster in the case of the quadratic law [Araya & Kiureghian, 1988].

Expression 2.8 gives the final distribution to be introduced in expressions 2.3 to 2.5 in order to compute the contribution to the final seismic hazard of the earthquakes occurring in seismic source *i*. As it is clear this distribution is truncated for values between *m0* and *mu* meaning that the integral between those limits equals one.

2.3 Seismic ground motion attenuation model

Another important issue of the PSHA is the complex phenomenology of propagation and attenuation of the energy released in the source that reaches a particular site.

Typically the decreasing of intensities of seismic strong ground motion with distance, from the source to the site, is attributed to two main causes: geometric and viscoelastic attenuation. The first one is related to the fact that seismic waves cross a greater volume of earth crust as the distance from the source increases. The second one is the result of the anelastic behaviour of the materials that compose the propagation medium.

In PSHA attenuation is generally considered as a random phenomenon and that is reflected in the mathematical procedures by the conditional probability $P(Y>y|m,R)$.

Araya & Kiureghian [1988] suggest the general formula to idealise attenuation:

$$Y = Z_y \cdot f(M, R, \mathbf{p}) \tag{2.9}$$

where Y is the strong motion parameter to be predicted; Z_y is a random variable representing the uncertainty in Y; R is a measure of distance from the source to the site; M is the magnitude that describes the size of the earthquake and **p** is a vector representing a set of parameters that can characterise the earthquake source, the wave propagation path, and the local site conditions (topography and soil effects).

Typically Y is taken as the maximum peak ground acceleration, velocity or displacement. Moreover the random variable Z_y, accounting for the scatter in the registered data and representing the uncertainty in the predicted values, is usually assumed to be Log-normally distributed.

Multi-regression analysis is use to fit semi-empirical attenuation relationships to data of strong ground motion records registered during earthquakes at stations distancing from the source from few kilometres to few hundred kilometres, and for events of several magnitudes.

A lot of research has been done in this field and many empirical relations have been purposed, generally valid for broad regions from where the data is originated, and to the domain covered by the epicentral distances and magnitudes used in the regression analysis. However, instrumental data covers only few regions in the world and the attenuation models estimated to one region must be applied to other regions with similar local soil conditions. This is the case of Portuguese region.

Several frequency-dependent attenuation relationships, with PSV, PSA or SA response variables, have been published that allow carrying out seismic hazard analysis in terms of spectral ordinates, at different periods, all with the same hazard level (URS) [Abrahamson & Silva, 1997, Ambraseys *et al.*, 1996; Ambraseys & Simpson, 1996; Boore *et al.*, 1994, Crouse & McGuire, 1996; Johnson, 1973; Joyner & Boore, 1982; Kawashima *et al.*, 1984; McGuire, R.K., 1977, Sabetta & Pugliese, 1996].

To accomplish the goals of the present project the probabilistic seismic hazard evaluation included frequency-dependent attenuation relationships related to displacement spectral ordinates, derived for Europe [Borzi, *et al.*, 1998] and briefly described in section 3.2.

2.4 Earthquake time occurrence model

As it was pointed out the density probability function $f_M(m)_i$ in expression 2.3 only refers to the relative number of events as function of magnitude, in the source zone i, and in a specified period of time, ranging from a minimum positive value $m0$ to a maximum value mu. In other words, that probability can be interpreted as conditional, regarding the occurrence of an earthquake in source zone i with magnitude between those limits. The integral of $f_M(m)_i$, from $m0$ to mu, must be always equal to one. On the other hand, the term $P(Y>y|m,R)$ in the same expression is obviously conditional on the occurrence of earthquake with a given magnitude and focal distance.

Consequently, values of $P(Y>y)_i$ (given by 2.3) also translate the probability of exceeding intensity y, conditioned on the occurrence of an earthquake in seismic source i, with magnitude between the limits $m0$ and mu; so far nothing was said about the probability of the occurrence of this event.

However, it is clearly recognised that the occurrence of earthquakes is a time dependent stochastic process meaning that the probability $P(Y>y)_i$ should always be combined with a model of earthquake occurrence in time.

Although not always a valid assumption, the most simple and common used stochastic idealisation of time occurrences is the well-known Poisson process. The validity of such an idealisation is based on the following assumptions [Araya & Kiureghian, 1988]:

1. An event can occur at random and at any time.
2. The number of occurrences in non-overlapping intervals is independent.
3. The probability of occurrence of an event in a small interval Δt is proportional to Δt and is given by $\nu.\Delta t$, where ν is the mean rate of occurrence of events (assumed as constant). Furthermore, the probability of two or more occurrences in Δt is negligible.

The first two assumptions imply the basic property of Poisson processes known as the "lack of memory". That is, any occurrence at an instant in time is not affected by past occurrences nor does it affect any future events.

To include the stochastic model in the hazard analysis, let ν_i be the estimate of the annual mean rate of occurrence of earthquakes with magnitude greater then *m0* in a given seismic source zone *i*. Thus the mean rate of occurrence of an intensity greater then *y* in the site, defined as w_i, will be the simple product:

$$w_i = \nu_i \cdot P(Y > y)_i \tag{2.10}$$

Under the validity of the assumptions of a stochastic Poisson model for time occurrences, the probability of being exceeded, at least once, the reference intensity level *y*, for a specified time interval *L*, due to the seismicity of a source zone *i* is given by:

$$P(Y_L > y)_i = 1 - e^{-w_i \cdot L} \tag{2.11}$$

Final estimates of the probability of being exceeded, at least once, the reference intensity level *y*, for a specified time interval *L*, due to the random seismicity in the entire region covered by *n* source zones, are based in the Poisson process property of not being affected by the aggregation of *n* independent Poisson processes.

Thus, assuming that the time occurrence processes are independent among source zones, that is, the fact of an earthquake has occurred in any source zone doesn't affect the occurrence process in any other zone, then the occurrence rate of a global Poisson process can be determined by summing all contributions w_i :

$$P(Y_L > y) = 1 - e^{\left(-L \cdot \sum_{i=1}^{n} w_i\right)} \tag{2.12}$$

Of course the applicability of this last expression depends also on the validity of the assumptions assumed for the Poisson process outlined above. Moreover, those must be extended to the region covered by all the seismic sources and, besides, the Poissonian basic property of time independence of events must be understood in relation to all future earthquake occurrences in the entire region.

When the time reference interval equals one year, equation 2.11 gives the annual probability of exceedance. In this context the return period, $RP(y)$, is defined as the inverse of hazard annual probability of being exceeded, at least once, the reference intensity level y in the site, that is:

$$RP(y) = \frac{1}{1 - e^{\left(-L \cdot \sum_{i=1}^{n} w_i\right)}} \tag{2.13}$$

As mentioned before a Poisson process assumes the independence of events. This aspect implies some contradiction with generally accepted physical phenomenology for earthquake occurrences. In fact, if an earthquake is the consequence of a sudden release of gradually accumulated strains in the earth crust, it is obvious that time sequences of such events could not be strictly considered Poissonian. However, the reasonability of the approach of the Poisson process to the seismic time occurrence process depends, sometimes, on the convenient elimination of aftershocks and foreshocks from the time sequence of events.

In what concerns the evaluation of uniform risk spectra URSs, expression 2.11 can be generalised to [Campos-Costa & Pinto, 1997]:

$$P\left(S_j^L > s_j\right) = 1 - e^{\left(-L \cdot \sum_{i=1}^{n} w_{j,i}\right)} \tag{2.14}$$

where, in this case, $w_{j,i}$ is:

$$w_{j,i} = \nu_i \cdot P\left(S_j > s_j\right)_i \tag{2.15}$$

and j stands for each frequency component of seismic ground motion.

2.5 Seismic hazard computation

Taking into account what was mentioned in the last sections it is now possible to present, in a more explicit form, the final expressions associated to the PSHA that must be implemented in a computer code. Of course, those expressions are valid for the set of assumptions assumed in all previous sections.

Considering the case of seismic hazard evaluations in terms of PGA, expression 2.11 must be changed to:

$$P(PGA_L > pga) = 1 - e^{\left(-L \cdot \sum_{i=1}^{n} w_i\right)} \tag{2. 16}$$

where, taking in account expressions 2.4, 2.8, 2.9 and 2.10, w_i is given by:

$$w_i = \nu_i \cdot \int_R \int_{m0_i}^{mu_i} \left\{ \begin{array}{l} [1 - \Phi(\ln(pga), \ln(PGA), \sigma_{PGA})] \cdots \\ \cdots k_i \cdot \left[-(\beta 1_i + 2\beta 2_i \cdot m) \cdot \exp\left(\beta 1_i \cdot (m - m0_i) + \beta 2_i \cdot \left(m^2 - m0_i^2\right)\right)\right] \end{array} \right\} \cdot dm \cdot dR \tag{2.17}$$

Cornell [1971] and Merz and Cornell [1973] performed analytically the integration on magnitude in equation 2.16 In general, the integration on spatial relationship between the source and the site is evaluated numerically in world-wide divulged PSHA computer codes [*e.g.* McGuire, 1976].

2.6 Hazard consistent analysis

Using Ishikawa approach [Ishikawa *et al.*, 1988] the expected values of magnitude *M* and focal distance *R*, could be assessed by the Bayes theorem. For a pair (*M*, *R*) it can be written:

$$E(M|Y > y) = \frac{\int_m \int_r m \cdot P(Y > y|m, R) \cdot f_M(m) \cdot f_R(r) \cdot dm \cdot dR}{\int_m \int_r P(Y > y|m, R) \cdot f_M(m) \cdot f_R(r) \cdot dm \cdot dR} \tag{2.18}$$

$$E(R|Y > y) = \frac{\int_m \int_r r \cdot P(Y > y|m, R) \cdot f_M(m) \cdot f_R(r) \cdot dm \cdot dR}{\int_m \int_r P(Y > y|m, R) \cdot f_M(m) \cdot f_R(r) \cdot dm \cdot dR} \tag{2.19}$$

where the values $E(M|Y > y)$ and $E(R|Y > y)$ express the conditional expected value of magnitude and focal distance given that a certain level of *Y*, that is *y*, is exceeded. This level is related to a certain probability o exceedance by the hazard curve.

Another way to assess the most probable pair of parameters (*M*, *R*) is to perform the probabilistic desagregation of magnitude and distance [McGuire, 1995].

3. MODELLING OCCURRENCE PROCESSES

3.1 Portuguese time and magnitude occurrence processes

The occurrence process in each source zone was characterised by the Poisson distribution and by the Gutenberg-Richter distribution of magnitudes, which are results achieved in another ENVIRONMENT project, entitled "Theoretical Research in Earthquake Prediction and Identification of Zones of Seismic Potential" (EV5V - CT94/0443).

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 report, but for reasons of completeness, as these are necessary inputs to the hazard estimate performed in chapter 4, a summary of the parameters of the occurrence process is presented herein.

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

Data on instrumental and historical earthquake catalogue, for Portuguese region, were considered. This catalogue covers a long period of observation (almost 2.000 years), allowing to model the distribution of seismic events by time and size.

The geographical area of analysis was subdivided into seismic source zones, taking into consideration the earthquake history, and the knowledge about tectonic processes causing seismic activity.

The model of 12 seismic source zones illustrated in figure 3.1 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. As it can be seen in figure 3.1, seismicity in continental region is diffuse, showing little correlation with neotectonic structures. In consequence, broader areas were adopted. Sousa [1996] presented the seismic source model used herein. A detailed description and discussion of the model can be found in that reference. Note that 5-5A means zone 5 minus zone 5A; the same applies to zone 6 and 6-6A.

In each zone the instrumental earthquake time sequence, without aftershocks, was modelled as a Poisson process (table 3.1) and the validity of this process was studied [Oliveira & Sousa 1999].

The Gutenberg-Richter law was the magnitude-recurrence relationship used to describe the frequency of earthquakes within a range of different sizes or magnitudes, in a seismic source zone, over a period of time. The parameters of the Gutenberg-Richter law were estimated applying simple linear regression techniques (table 3.1).

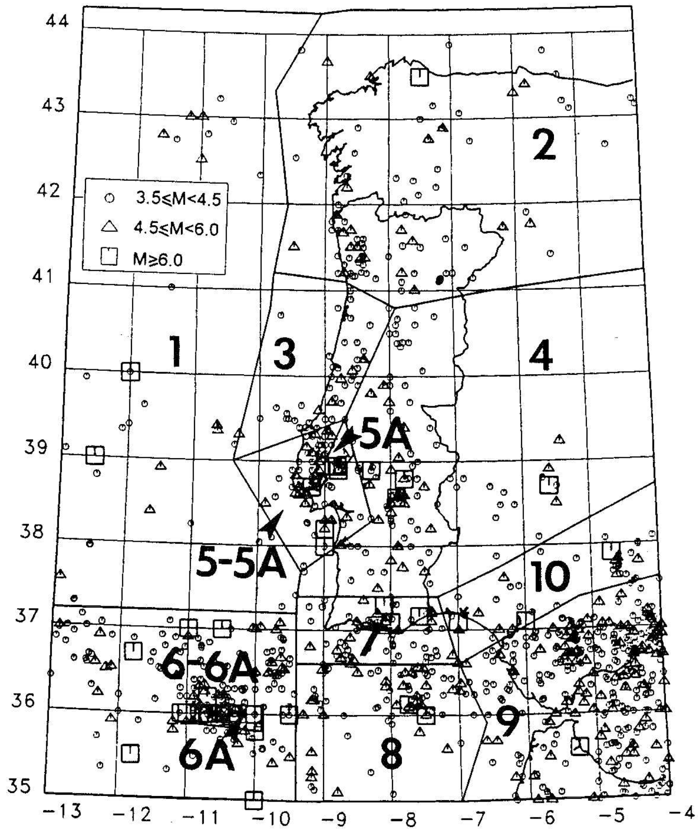

Figure 3.1 - Earthquake epicentres, 33 AD-1991, M ≥ 3.5 [Sousa et al., 1992] and seismic source model [Sousa, 1996].

Table 3.1 - Maximum magnitude, number of earthquakes per year, estimates of b-value of 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

3.2 Strong ground motion process

The strong motion database for European earthquakes was compiled by Ambraseys *et al.* [1996] and adapted by Bommer *et al*. [1998] for the derivation of frequency-dependent attenuation equations for ordinates of displacement response spectra. The strong motions were recorded at sites grouped at different local geological conditions.

Borzi [1988] adopted the following expression for the regression analysis for each spectral ordinate:

$$\ln(y) = C_1 + C_2 \cdot M_S + C_3 \cdot r + C_4 \cdot \log(r) + \sigma \cdot P \tag{3.1}$$

where y is the maximum displacement response of one degree of freedom system with a given period; σ is the standard deviation of log(y), P is a parameter that takes the value of zero when the median value of log(y) is considered, and 1 for the 84-percentile value of log(y); M_S is the surface-wave magnitude; $r = \sqrt{d^2 + h_0^2}$ where d is the shortest distance from the station to the surface of the fault rupture in km; h_0 C_1, C_2, C_3 and C_4 are regression constants for each period (the index j present in 2.14 and 2.15 expressions is omitted herein for the sake of simplicity).

Considering the effect of local site geology, that is a parameter that influence the amplitude and the shape spectra, the attenuation relationship can be re-written [Ambraseys *et al.,* 1996] as:

$$\log(y) = C'_1 + C_2 \cdot M + C_3 \cdot R + C_4 \cdot \log(R) + C_a \cdot S_a + C_s \cdot S_s + \sigma P, \tag{3.2}$$

where three classes of site geology were considered: rock (shear wave velocity averaged over the upper 30 m of the site, $V_S >$ 750 m/s), stiff soil (360 m/s $\leq V_S \leq$ 750 m/s) and soft and very soft soil ($V_S <$ 360 m/s). The regression residuals were re-calculated according to the local site geology influence. Table 3.2 shows the values of *Sa* and *Ss* considering local site geology.

Table 3.2 – Values of Sa *and* Ss *according to site geological conditions.*

Site geology	*Sa*	*Ss*
Rock	0	0
stiff soil	1	0
very soft soil	0	1

Borzi *et al* [1998] present the regression coefficients for the elastic displacement spectra (ξ=1%). Those site-dependent spectra cover a range of oscillator periods between 0,05 and 3,0 sec.

Figure 3.2 shows the median elastic displacement spectrum and the spectra with $\pm 1\sigma$ for an earthquake of magnitude 7,0 and r = 40 km. It is visible in this figure the large dispersion of the regression.

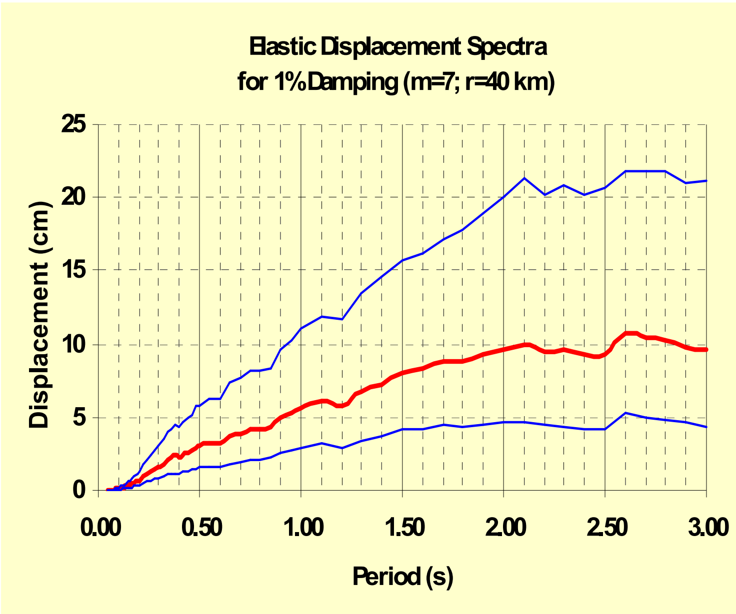

Figure 3.2 – Median of elastic displacement spectrum and elastic displacement spectra ±1 σ.

4. APPLICATION TO LISBON

An application of the methodology described in chapter 2 was made to the Lisbon area with the parameters of seismic occurrence characterised for Portugal in chapter 3.

Figure 4.1 presents the Uniform Displacement Spectra computed for Lisbon, considering an average stiff soil, 1% damping and 475 and 975 years return periods.

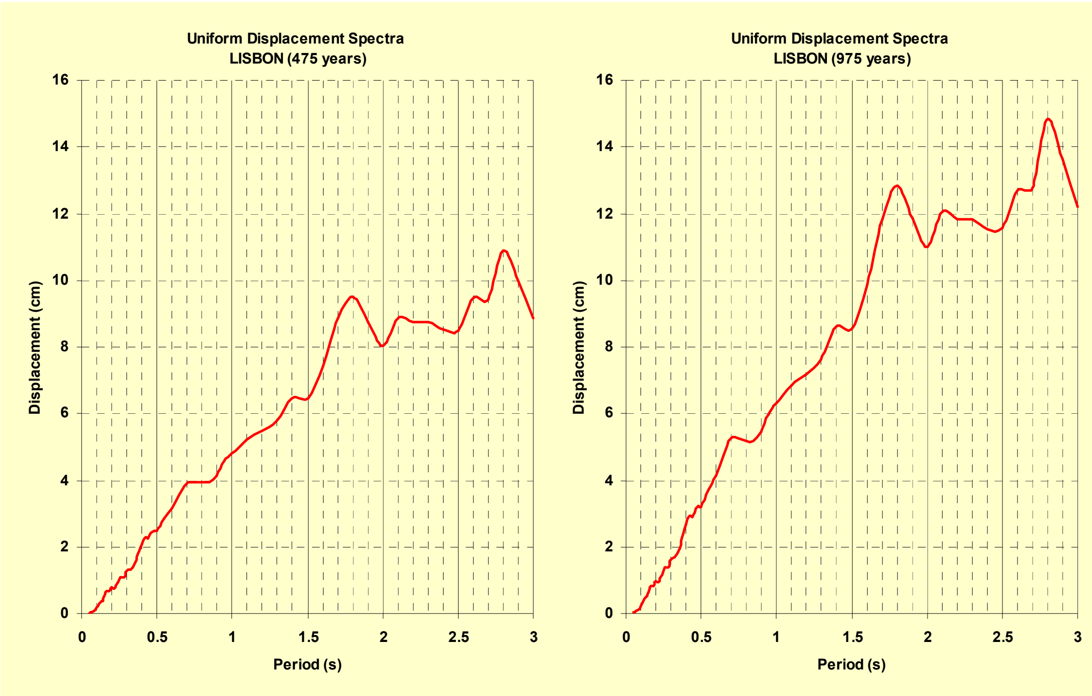

Figure 4.1 – Uniform Displacement Spectra (475 and 975 years).

Figure 4.2 presents the correspondent expected values of magnitude and epicentral distance for the 475 years return period.

From those figures one can conclude that:

1. The main seismic scenario, characterised by a pair of magnitude and epicentral distance, contributions are not the same over the entire period range. From low to high periods expected values of magnitudes and epicentral distances tend to increase. Magnitude and epicentral distance increases considerably, from 4,5 to 6,0 and from 10 to 80 km, in the period range below 0,9 sec. Thereafter, for periods greater than 1.0 sec., the values of magnitude tend to be more constant varying from 7,0 to 7,8, while the values of expected epicentral distance varies from 180 to 280 km. In the period range between 0,9 and 1,0 sec. it is clear a discontinuity in both expected values.

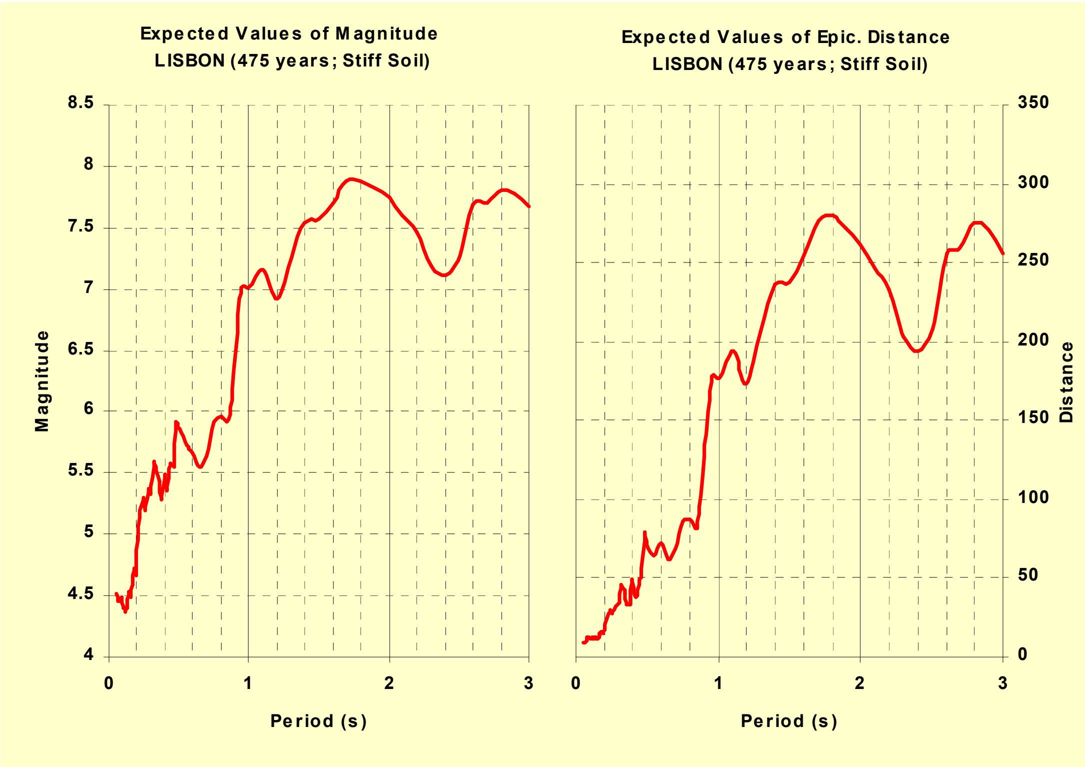

Figure 4.2 – Expected values of magnitude and epicentral distance (475 years).

2. Low period response spectra ordinates are induced by low magnitude and short distance earthquakes, whereas high period ordinates are influenced by higher magnitude and longer distance earthquakes, meaning that the computed spectrum is not physically linked to an unique seismic scenario.

3. These two aspects arise from the basic criterion underlying the URS approach, which consists in considering the independence of each frequency component of the seismic ground movement (expression 2.14 and 2.15).

Those aspects are naturally linked to seismotectonic features of the region under analysis. If the seismicity of the region is mainly controlled by a unique tectonic structure the issues stressed above are not so important. On the other hand, if the seismicity of the region is induced by complex seismotectonic structures, one should consider, in hazard studies, the possibility of modelling different scenarios in order to avoid that type of inconsistencies.

This is the case of the Portuguese tectonic environment in which two important source mechanisms may be distinguished:

1. The earthquakes originated by the movement between the Eurasian and African plates designated by interplates events. In particular, in the Gorringe bank the movements

associated to this boundary caused severe events which affected the Iberian Peninsula and the Northern Africa, such as 1755 and 1969 earthquakes.

2. The earthquakes originated in faults inside the Eurasian plate designated by intraplate events. The Benavente earthquake of 1909, and probably the 1531, January 26 earthquake, are examples of intraplate events.

One may expect that time duration and frequency content of strong ground motion originated by interplates and intraplate events are different: long duration and lower frequency content for the former and short duration and higher frequency content for the latter. One also may expect that intraplate events affecting the site have their epicentres mainly at short distance of Lisbon and that interplates events have their epicentres mainly at long distance of the site.

The criterion to desegregate these two scenarios consists in splitting the spatial integration in expressions 2.4 and 2.5 in two domains: short distance earthquakes (0<*r*<50km) and long distance earthquakes (*r* > 50 km) as shown in figure 4.3.

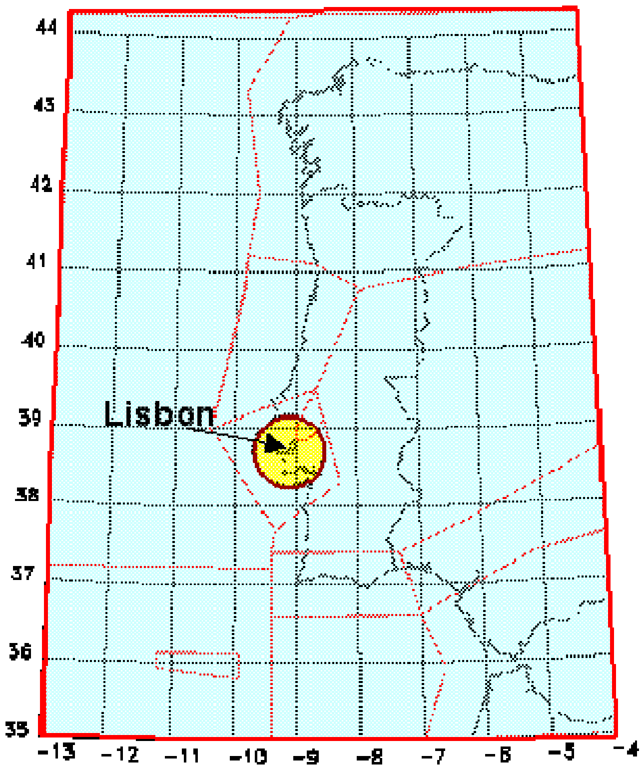

Figure 4.3 – Source model for long and short distance scenarios.

New results were obtained, for the same Lisbon site and the same return periods, considering however the two above mentioned scenarios. Figures 4.4 presents URS for 475 years return period and short and long distance scenarios. Figure 4.5 presents the correspondent expected values of magnitude and epicentral distance. In those figures it is also plotted the previous results already shown in figures 4.1 and 4.2.

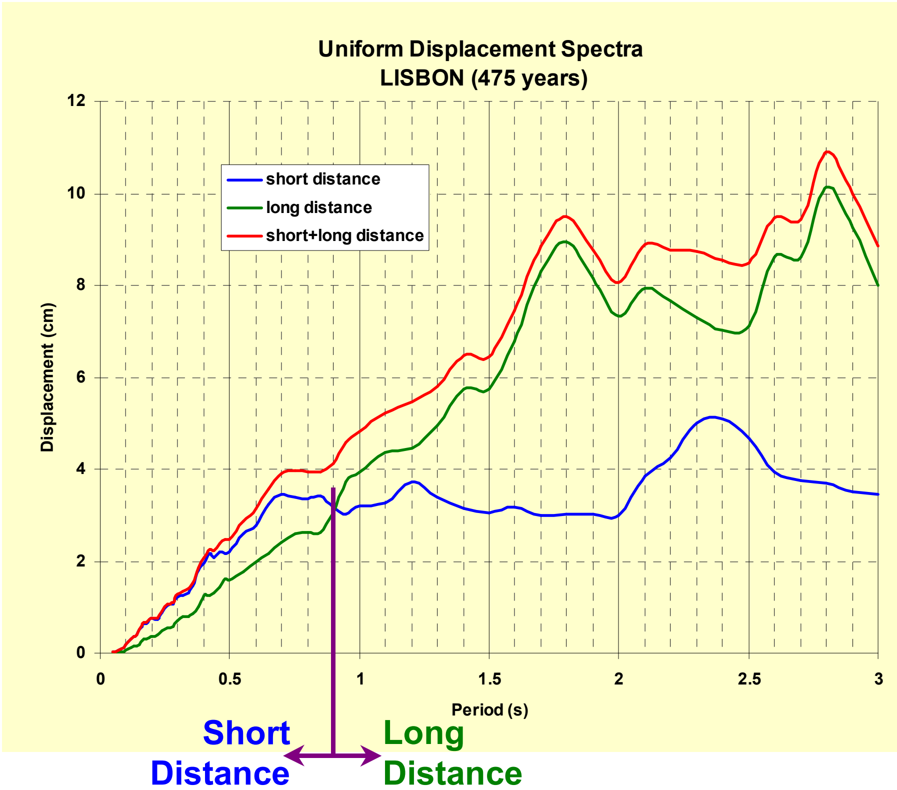

Figure 4.4 – Uniform Displacement Spectra (475); short and long distance scenarios.

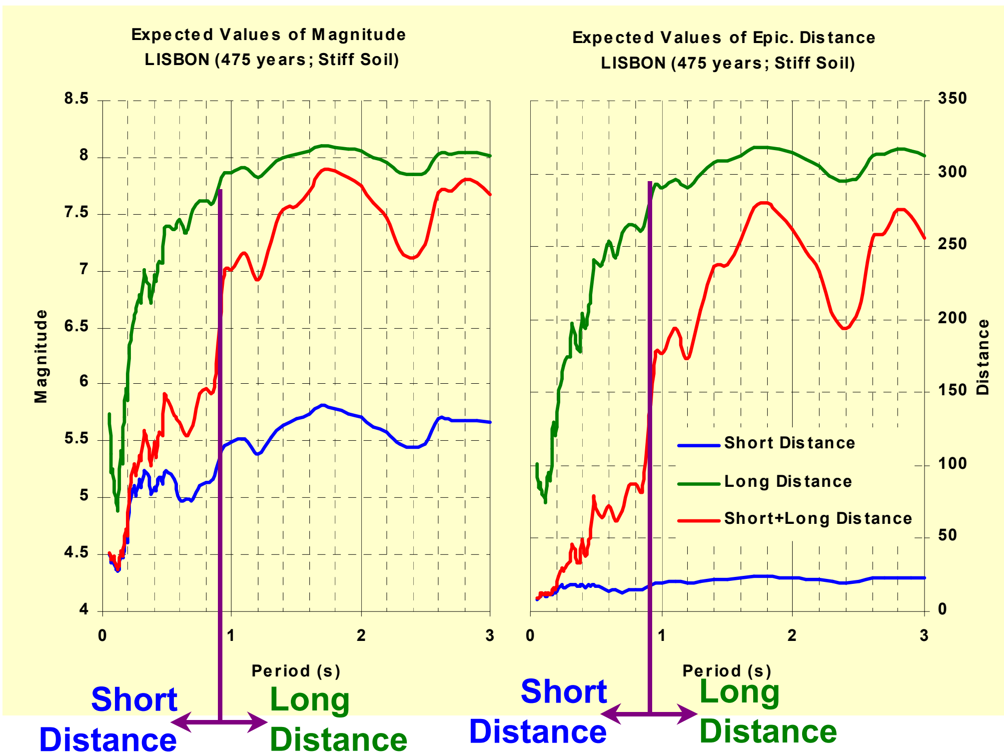

Figure 4.5 – Expected values of magnitude and epicentral distance (475 years); short and long distance scenarios.

From these two figures it can be concluded that:

1. For periods below 0,9 sec., short distance scenarios presents larger spectral displacement than the long distance scenarios, whereas for periods above that limit the opposite is observed.
2. For short distance scenarios and for periods below 0,9 sec. expected values of magnitude varies between 4,3 and 5,2 and expected values of epicentral distance are almost constant around 15 km.
3. For long distance scenarios and for periods above 1,0 sec. expected values of magnitude varies between 7,9 and 8,1 and expected values of epicentral distance varies from 270 km to 320 km.

It is clear that the two distance scenarios influence in a different way the two period ranges. On the other hand, the enveloping curve for the short and long distance scenarios, follows closely the largest of each one of the two separate curves for each single distance scenario, except for the transition period range around 0.9 sec.

At this transition range, the ratio between the envelope and the largest individual curve increases sharply to around 1,25, whereas in the remaining period ranges it presents values in the order of 1,10 (with another exception in the vicinity of 2,4 sec.).

Thus, it is observed that the Uniform Displacement Spectra is more easily applicable for a unique seismic scenario characterised by a pair of magnitude and epicentral distance.

Moreover, in the general methodologies used for PSHA to assess the Uniform Response Spectra for the specification of a seismic action for design purposes, it is important to take into account the possibility of existence of independent seismic scenarios. This is particularly the case if several independent seismotectonic features control such seismic action. The spectrum computed by the probabilistic convolution of those independent scenarios may overestimate the spectral ordinates of seismic action.

A feasible solution to overcome this problem could be the splitting of the PSHA into several scenarios associated to the more important seismotectonic features.

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