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A New Approach for Physically-based Probabilistic Seismic Hazard Analysis for Portugal

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Abstract. Probabilistic seismic hazard analysis (PSHA) is nowadays the more complete analysis method to estimate the seismic input for structural analysis. However, it is strongly influenced by seismogenic parameters and attenuation equations. Here PSHA using empirical Green's functions (EGFs) with 2+2 variables is carried out, which are correlated through the moment magnitude. This combination, already known as "physically-based PSHA (pb-PSHA)", is an original approach that should be disseminated because it provides a good alternative in countries where the seismogenic zones and attenuation equations are not well known. The proposed model is based on linear faults, random, periodic, impulsive, linear source functions, and a punctual hypocentre. Differential equations are explained. Results are shown in terms of new seismic parameters, specific return periods and ground accelerations. The studied country is Portugal. It appears to the authors that no study has been published about pb-PSHA for Portugal.

Keywords. PSHA; EGF; pb-PSHA; importance factors; attenuation equations; Portugal.

1 Introduction

The definition of seismic inputs has always been of interest to both geophysicists and engineers [79]. There are several procedures that provide seismic inputs for structures designing. These procedures can be deterministic, using elastic spectra from codes [7,8], synthetic spectra by attenuation equations [5,47], deterministic seismic hazard analysis [30,44], artificial accelerograms obtained from power spectrum density functions [23,26], seismic coefficients by amplification of inertial forces [35], time-history analyses from database [19,21], spectrum compatible analyses by scaling factor [36,42,73].

The probabilistic procedures can be either the probabilistic seismic hazard analysis (PSHA) by Cornell model [2] or the physically-based PSHA (pb-PSHA) [37,65], which is treated in this paper.

The pb-PSHA is mainly based on the PSHA, which is nowadays the more complete method to estimate the seismic input because it accounts for the seismotectonic and geological context and the probability of occurrence of earthquakes [30,38,39,40,41,43,45,73].

Pb-PSHA follows the same procedures of standard PSHA with only one difference: attenuation equations are not used and are substituted by empirical Green's functions (EGFs) and computation of physically based seismograms and direct analysis accounting the hazard for structures [14].

EGFs allow to directly calculate the ground displacement at a site, defining wave path from the seismic source to the ground. However, it is not possible to know the characteristic of the soil [22].

The studied area is Portugal where seismic activity is high. Since the 1755 Lisbon earthquake, several studies, including old ones [56,57,58,59] up to the most recent [60,61,62], have been developed. For Portugal, some papers have been published about PSHA [5,6,63,64] but it appears to the authors that no study has been published about pb-PSHA.

The motivation of this study is the choice of a model and parameters to be correctly used.

“Random” uncertainties are related to the inherent randomness of the studied phenomena, whereas the “epistemic” uncertainties are related to the lack of knowledge of the models [9,10].

Random and epistemic uncertainties are studied in stochastic analyses, which are used to solve problems that cannot be deterministically solved because models are not completely known, or data are not available. However, when epistemic uncertainties are predominant with respect to random uncertainties, it is difficult to choose a unique model.

The specific motivations are summarized in the following three points.

1. Lack of a well-calibrated attenuation equation for Portugal. In this sense the use of EGFs to directly calculate the ground accelerations is advisable. In literature there are four attenuation laws for Portugal of which three are expressed in terms of seismic intensity due to the scarcity of instrumental data [46,47,66] and one is expressed in terms of spectral accelerations [5] (see Table 1).

Table 1. Attenuation equations for Portugal.

Attenuation equation	Year
$I = 0.98 + 0.85 M - 0.23 \ln(R) - 0.006 R^a$	1997 [66]
$I = 6.8 + 1.13 M - 1.68 \ln(R + 14)$	1999 [46]
$\log_{10} \text{PGA} = -0.74 + 0.55 M - 0.002 \log_{10} R - 0.61 R + 0.25$	2007 [5]
$I = -1.9438 \ln(R) + 4.1 M - 9.5763$	2014 [47]

Note: I = Intensity. M = Considered magnitude. R = Considered distance. PGA = Peak ground acceleration.

^a Values estimated for a specific zone: ZS5 for EC8 model (see Fig. 1).

These equations are very different from each other although they should be used for the same country. In this sense it is difficult to rely on these equations. In [48,49] other attenuation equations calibrated by using Portugal data are presented, however, these are not defined for this country.

2. There are four valid models for Portugal, what makes it difficult to choose the best. These models that characterize the seismogenic zones (ZS) are: Share, Ersta, EC8, Zesis [4,6,8] (see Fig. 1). In this sense, there are four models that provides different outputs, moreover, it has been noted in literature [6,64,66,67] that for the same seismogenic zones of the same EC8 model, different values have been obtained.

Figure 1. Seismogenic zones for Portugal: Share, Ersta, EC8, Zesis [4,6,8]

3. Inconsistency of the following relation: $PGA = \gamma_I \times PGA_R$, where γ_I is the importance factor and PGA_R is the reference PGA [7,8,50]. This relation correlates an acceleration (PGA) with the type of construction (e.g. agricultural buildings, schools, power plants). Given that, as mentioned in [50,76], γ_I is not related to the structure characteristics, this relation is inconsistent. Thus, the logic to correlate the structure (object to be designed at surface) with a PGA (seismic input in deep) should be exceeded because the two parameters are not correlated.

According to the authors, a more correct form to quantify the importance factor is treated in literature where this factor is calibrated as a function of the vulnerability of the structures, external loadings [75], evaluation of benefit/costs for the service-life [76], losses due to damage and failure of the structure [77].

2 Materials

2.1 Materials for seismic hazard

Four seismogenic zones have been selected, of which two are typically used only for Portugal, as the Share and Ersta [6], one is based on Eurocode EC8 [6,8] and the other includes the Iberian Peninsula Zesis [4].

From these seismogenic zones, data have been collected and used to calibrate new data regarding 6 specific seismogenic zones. In particular, this analysis is based on the associated

events that characterize the seismicity of each seismogenic zone for Zesis. The group of events has been divided in sub-groups ΔM_w , associated to a number of events with the same moment magnitude M_w , completeness period, completeness interval, frequency of events of similar intensity, mean annual rate of exceedance λ_c , return period $1/\lambda_c$, and $\log_{10}\lambda_c$.

The events provided by Zesis have already been processed for homogenization, declustering and completeness [3,30]. Therefore, these operations have not been repeated. Thus, all events have been taken as they are with the registered M_w and, for the completeness period, the oldest year has been considered.

λ_c of events with magnitude M_w is correlated by the following Gutenberg-Richter (G&R) law [1]:

$$\log_{10} \lambda_c = a + bM_w \quad (1)$$

where the b-value describes the ratio between the number of small and large events, whereas the a-value measures the level of seismicity.

Table 2 shows the selected ZSs regarding continental Portugal and the equivalence between them in terms of nomenclatures.

Table 2. Equivalences between the seismogenic zones (ZSs).

ZS for Share [6]	ZS for Zesis [4]	ZS for Ersta [6]	ZS for EC8 [6]
242 (Évora) ^a	10	C, E and Z3	4
245 (Algarve)	13	D	8
249 (Coimbra)	7	A and B	3
250 (Villa Real)	6	Z2 and B	2 and 4
251 (Lisbon)	9	B	5
255 (Braga)	2	Z1	2

^a In bracket is indicated a place of reference (city or region).

Table 3 lists the parameters collected from literature and obtained in this analysis. b-value ranges from 0.64 to 1.06 (underlined value). b-value is considered as the universality value, i.e. considering the reference value $b = 1.0$, when $b < 1.0$ the area is more dominated by large but

infrequent events and the small earthquakes have a lower frequency compared to the strong earthquakes.

Table 3. Comparison of the models (b-value).

ZS (Zesis)	b-value (Share) [6]	b-value (Zesis) [4]	b-value (Ersta) [6]	b-value (EC8) [6]	b-value (mean) ^a	b-value (this analysis)
10	1.00	1.00	0.99	0.82 (0.84) ^b	0.953	0.97
13	1.00	<u>1.06</u>	0.75	0.77 (<u>0.64</u>)	0.895	0.83
7	1.00	1.06	0.88	0.86 (0.89)	0.949	1.04
6	1.00	0.98	0.94	0.82 (0.84)	0.934	0.83
9	0.90	0.87	0.79	0.71 (0.95)	0.818	0.72
2	1.00	1.04	0.98	0.66 (0.84)	0.920	0.88

^a The mean value refers to the values of Share, Zesis, Ersta, EC8 (except values in bracket).

^b In bracket there are the values estimated for the same seismogenic zones and model by other authors [64,66,67].

It is possible to see that, in Table 3, by the EC8 model, two different values for each ZS have been estimated [6,64,66,67]. This clearly confirms the difficulty in estimating a unique value, although the model and the area are the same (the total mean difference is about 7%).

A difference between a mean of b-values calculated by Share, Zesis, Ersta, EC8 models and the b-values calculated in this analysis is 0.033 (3.75% error). This indicates a good calibration.

Figure 2 shows the G&R trend by Eq. (1) for each ZS for Zesis. The solid line is the R&G trend with $b = 1.0$ [20]. Each point represents the pre-defined sub-groups ΔM_w .

Figure 2. G&R of this analysis for each ZS for Zesis.

Table 4 shows a-values for all models. The range of a-value is 2.27 – 3.60 (underlined value). In fact, a-values are generally of the order of 3.0 [8]. A good calibration for a-values is more complicated because a small variation of b-values provides a large variation of a-values at $M_w = 0$. Here the difference is 0.252 (9.09% error).

Table 4. Comparison of the models (a-value).

ZS (Zesis)	a-value (Share) [6]	a-value (Ersta) [6]	a-value (EC8) [6]	a-value (mean) ^a	a-value (Zesis) ^b	a-value (this analysis)
10	3.32	2.97	2.94	3.078	3.51	3.58
13	3.00	<u>2.27</u>	2.56	2.610	3.41	2.35
7	3.10	3.22	2.64	2.987	3.13	3.05
6	<u>3.60</u>	3.45	2.94	3.328	3.31	2.48
9	3.40	3.03	2.41	2.947	2.90	2.06
2	3.30	3.56	2.64	3.167	3.80	3.09

^a The mean value refers to the values of Share, Ersta, EC8.

^b Estimated value from b-value.

Table 5 shows λ_c -values only for models with available data. This parameter, whose range is 0.04 – 0.32 (underlined value), is strongly influenced by the number of events to be considered with the same M_w . Here a poor calibration is obtained, with a difference of 0.07 (47% error). However, to quantify the error only data from Zesis were available.

Table 5. Comparison of the models (λ_c -value).

ZS (Zesis)	λ_c (Zesis) [4]	λ_c (this analysis)
10	0.28	0.28
13	0.13	0.13
7	0.16	<u>0.04</u>
6	0.19	0.09
9	0.24	0.16
2	<u>0.32</u>	0.19

2.2 Materials for Green's function

Two main input parameters are necessary to develop the EGF: the fault and the seismic source. In the ZSs, the fault is characterized by a dominant tectonic, stress regime and main focal mechanism. The distance from the epicentre and edge of the fault rupture area is $\Delta < 30$ km. The source provides a list of events with a specific location, seismic moment M_0 , M_w and other parameters listed in Table 6.

221

222 Table 6. Used seismic events retrieved from database [19,21].

Datum		Event		
Region:	Évora	Leiria	Lisbon	Lisbon
Date, time:	15/01/2018, 11:51	30/04/1999, 9:00	17/08/2017, 6:44	16/10/2000, 3:22
Latitude, longitude:	38.79, -7.93	39.82, -8.96	39.11, -8.92	38.70, -9.15
ZS for Zesis [4]:	10	7	9	9
Depth, Δ (km):	11.0	22.9	12.0	20.3
M_w :	5.4*	4.7*	5.0*	4.0*
M_0 (N $\times$ m):	1.49×10^{24} *	1.39×10^{23} *	3.85×10^{23} *	1.30×10^{22} *
Style of faulting:	N/A	N/A	N/A	N/A
PGA (cm/s ²):	1.24	28.75	0.152	5.70
PGV (cm/s):	0.09	2.11	0.01	0.33
PGD (cm):	0.01	0.14	0.0	0.02
PSA _{max} :	6.79	110.17	0.639	16.37
f _{max} (Hz):	1.691	1.27	1.721	2.216
f _{min} (Hz):	0.003	0.012	0.03	0.06
T _s (s):	27.24	13.66	46.04	16.61

223 Note: *Estimated value. N/A = Not available. PGA = Peak ground acceleration. PGV = Peak
 224 ground velocity. PGD = Peak ground displacement. PSA_{max} = Maximum pseudo-spectral
 225 acceleration. f = Frequency of the Fourier amplitudes. T_s = Significant duration (5-95% Arias
 226 intensity [78]).

227

228

229 For some events, database [21] provides a local magnitude M_L instead of M_w , which is mostly
 230 used for this type of analysis. From the literature [31,32], it is known that a unique global
 231 relation between M_L - M_w does not exist. However, a more recent relation has been calibrated
 232 [68], in which a discrepancy of ~ 0.49 has been noted. M_0 has been calculated in accordance to
 233 the literature [33].

234

235 The style of faulting is not available (N/A) by database. However, the reference stress regime
 236 can be taken from the respective ZSs where the event happened.

237

238 Figure 3 shows accelerograms in time $\ddot{u}(t)$, the Fourier amplitude as function of the frequency,
 239 f, and the PSAs in function of structural periods, T. Four earthquakes have been processed by
 240 software [24] and plotted for T_s of the 5-95% Arias intensity [78]. Although they are quite

“clean” recordings, the linear baseline correction and filtering with butterworth type filter and bandpass configuration (0.50–25.0 Hz) have been applied.

Figure 3. Accelerograms $\ddot{u}(t)$ in the time t (a); Fourier amplitude vs. f (b); PSA vs. structural period T (c) for four selected earthquakes.

Fig. 4 shows the location of the epicentre (star) and the station (triangle) where the PGA has been registered of the four earthquakes. It is possible to see that the distances are so great as to pass from a ZS to other ZS. The distances are, from left to right in Fig. 4, 14.2 km, 181.6 km, 185.5 km, 80.8 km.

Figure 4. Location of the epicentre (star) and station (triangle) for the four earthquakes.

Other events have been selected in order to understand, in a qualitative way, seismic registration in Portugal. From these events the relations in Table 6 between M_w/M_0 , M_L/M_w have been calibrated. These events, that happened in Azores islands (outside of the considered seismogenic zones) at 10.0 km depth, are:

1. 01/08/2000, 4:35 date; 38.79, -29.0 latitude, longitude; 5.1 M_w ; $M_0 = 5.10 \times 10^{23}$ N $\times$ m; strike-slip style of faulting.
2. 09/07/1998, 5:19 date; 38.65, -28.62 latitude, longitude; 6.2 M_w ; $M_0 = 1.60 \times 10^{21}$ N $\times$ m; strike-slip style of faulting.
3. 27/06/1997, 4:39 date; 38.33, -26.68 latitude, longitude; 5.9 M_w ; $M_0 = 6.8 \times 10^{24}$ N $\times$ m; normal style of faulting.
4. 01/01/1980, 16:42 date; 38.81, -27.78 latitude, longitude; 6.9 M_w ; $M_0 = 2.82 \times 10^{26}$ N $\times$ m; strike-slip style of faulting.

3 Methodologies

The general methodology is divided in two processes, i.e. PSHA + EGF, which are correlated to each other by M_w , that provide pb-PSHA (see Fig. 5). By this methodology the first and second problem described in the introduction could be overcome.

Figure 5. General methodology for PSHA + EGF $\equiv$ pb-PSHA.

The general methodology, in Fig. 5, illustrates the main inputs of both models, that inserted in the corresponding process, provides the outputs. Both models are correlate to M_w , which is treated as a probabilistic parameter in PSHA and as a physical parameter in EGF.

For the PSHA the input data are M_w and year, whereas the output data are a-value, b-value, λ_c . Theses parameters have already been explained in a previous section. For the EGF the input data are M_0 and M_μ (latter explained), whereas the output data are the ground motions $u(x,t)$.

Fig. 6 shows the interdependencies of all parameters involved in both methods. The parameters in green indicate that can be calculated in direct way, in yellow in indirect way and in red are not calculated. These parameters are treated in literature [51,54,74].

Figure 6. Interdependencies of parameters directly calculated (in green), indirectly calculated (in yellow), no calculated (in red).

3.1 Seismic hazard

The PSHA is based on the Cornell method [2] and the Poisson distribution [34]. A truncated exponential probability density function (PDF) at the minimum, $M_{w,min}$, and maximum magnitude moment $M_{w,max}$, is used. The probability of exceedance P_e of several magnitudes, $\mu_{w,i}$, associated to a specific seismogenic zone and correlated to a PDF for source-side distance r in a range $r_{min} \leq r \leq r_{max}$, $f_R(r)$, is described by [3,73]:

$$P_e[M_w > \mu_{w,i}] = \int_{r_{min}}^{r_{max}} P_e[M_w > \mu_{w,i}] f_R(r) dr = \int_{r_{min}}^{r_{max}} \left(\frac{e^{-(\beta(\mu_{w,i} - M_{w,min}))} - e^{-(\beta(M_{w,max} - M_{w,min}))}}{1 - e^{-\beta(M_{w,max} - M_{w,min})}} \right) \frac{r}{L\sqrt{r^2 - \Delta^2}} dr \approx \frac{e^{-(\beta(\mu_{w,i} - M_{w,min}))} - e^{-(\beta(M_{w,max} - M_{w,min}))}}{1 - e^{-\beta(M_{w,max} - M_{w,min})}} \quad (2)$$

where L is the fault length, Δ is the vertical projection of the fault at ground surface, $\beta = b \log_e 10$. PDF of $f_R(r)$ is expressed by an equation that models a shallow fault as a linear source.

The probability of not-exceedance P_{ne} and the return period $T_{\mu_{w,i}}$ are defined, respectively, as:

$$P_{ne}[M_w \leq \mu_{w,i}] = e^{-(\lambda_c \times P_e)} \quad (3)$$

$$T_{\mu_{w,i}} = \frac{1}{1 - P_{ne}} \quad (4).$$

3.2 Empirical Green functions

3.2.1 Basic hypotheses of the model

The use of EGFs is based on the literature [17,28,52] where EGF only represents the medium, through the effects of propagation. EGF is a vector record that includes the seismic source. For the definition of seismic source, events small enough are used that the frequency of interest is below the source corner frequency, so that the source of the EGF is a step function, which it is removed by deconvolution. Therefore, EGF is convolved with the source function. If it is not possible to find events small enough, it is deconvolved out a Brune source [37], which work for small magnitude (< 4.0), to obtain the propagation of EGF.

In this study, the approach is similar but somewhat different. Here, the EGF is a vector that accounts for the contribution of wave equations, whereas the source function is defined by another function that is convoluted with the EGF. In this way, EGF is inserted directly into the elasto-dynamic equation, as detailed in the following section. Often, the source is at a point in space or time, so that the seismic source contains delta functions and is easily integrated. A feature of this formulation is that the principle of reciprocity, which says that the source and the receiver can be interchanged, emerges directly [28].

3.2.2 Theory

The general analysis of displacements discontinuities across an internal surface Ω is treated in this section. Here, the discussed aspect is to pass from a surface Ω to a line x' (see Annex).

EGFs for a time-dependent t differential operator $\mathcal{L}(u(x, t))$ over the region Ω is defined to be a solution $g(x', t'; x, t)$ of $\mathcal{L}(g(x', t'; x, t)) = \delta(x - x')\delta(t - t')$, by the Dirac delta function δ [17], that satisfies the given homogeneous boundary conditions $\mathcal{B}(u(x, t))$ [17,18,25]. A particular solution of $\mathcal{L}(u(x, t)) = f(x, t)$ with homogeneous boundary $\mathcal{B}(u(x, t))$ in a general medium can be obtained by performing a convolution integral:

$$\int_0^\infty dt' \int_{x' \in \Omega} f(x', t') g(x', t'; x, t) dx' \quad (5).$$

The elastic-dynamic equation of an earthquake and its ground motions is here represented. The ground displacement, $u(x, t)$, in the direction $\hat{x}_n$, at location x and time $t > 0$ is [11]:

$$u(x, t) = \int_{-\infty}^\infty \int_0^\infty f(x', t') g(x, t; x', t') dx' dt' \quad (6)$$

where $f(x', t')$ is a seismic source function in the $\hat{x}_q$ direction, at location x' ($\equiv L$ in Eq. (2)) and time t' , and $g(x, t; x', t')$ is the Green's function tensor. The Green's function tensor is the contribution to the displacement in the $\hat{x}_n$ direction from a unidirectional unit-impulse in direction $\hat{x}_p$ (see Fig. 8(b)).

The integrals of Eq. (6) provide the total response due to the source distribution. In this case, the source is limited in the space x' and time t' . Therefore, the integral is not calculated over the source region Ω .

The use of the $g(x, t; x', t')$ provides a solution for a partial differential operator $\mathcal{L}(u(x, t))$ with boundary conditions $\mathcal{B}(u(x, t))$ in the range $x_{\min}$ to $x_{\max}$, described as $g: \{\mathcal{L}(u(x, t)), \mathcal{B}(u(x, t)), u(x, t), \{x, x_{\min}, x_{\max}\}, t, \{x', t'\}\}$ [15]. To solve the nonhomogeneous (i.e. $\neq 0$) wave equation [12,69] using g , the solution of $\mathcal{L}(u(x, t))$ as an one-dimensional x equation of transversal body waves β_s [16] with unbounded, $\mathcal{B} = 0$, the relation becomes $g: \{\frac{\partial^2 w(x, t)}{\partial x^2} - \frac{1}{\beta_s^2} \frac{\partial^2 w(x, t)}{\partial t^2}, \mathcal{B} = 0, w(x, t), \{x, -\infty, \infty\}, t, \{x', t'\}\}$, whit $\beta_s^2 = (\mu/\rho)^{1/2} = 1$. μ is the Lamé constant and ρ is the material density.

g solution is:

$$g = -\frac{1}{2} \Theta[(-t' + t) - |-x' + x|] \quad (7)$$

where $\Theta(x, t, x', t')$ is the Heaviside theta step function, which is assumed as a displacement discontinuity [28]. Θ is a multidimensional function, which is 1 only if none of the x, t, x', t' are not positive. $|\cdot|$ is the modulus.

389

390 Eq. (7) represents the solution of the wave equation-through Θ function. By substituting Eq. (7)
 391 in Eq. (6) with $f(x', t') = 1$, it is possible to plot the trend due to the amplification of the Green's
 392 function g as shown in Fig .7.

393

394 In fact, the solution of Eq. (6) is a space and time convolution and the spatial part is two (or
 395 three) dimensional, and that will affect the seismograms. However, this amplification quantifies
 396 the physical nature of the seismic source. Therefore, a reduction it is not necessary.

397

398 Figure 7. Plot of Eq. (7) in Eq. (6) with $f(x', t') = 1$, integrated for $-\infty < x' < +\infty$ and $t' \geq 0$.

399

400 Eq. (6) contents the characteristics of the source related to released energy. However, also by
 401 using Eq. (7), it does not describe the ground motion. Therefore, a further function must be
 402 introduced. The key of the problem is to define a nonhomogeneous term for $f(x', t')$ to describe
 403 the seismic source function in spatial x' and time t' distribution of slip along the fault [53].

404

405 Here, $f(x', t')$ is one of the following four types of functions (random, impulsive, periodic,
 406 linear).

407

$$408 \quad f(x', t') = \begin{cases} \sum_{i=1}^n a_{h,i} (\sin(\omega_i t' + \phi_i) + \cos(\omega_i x' + \phi_i)) & \text{Random} \\ a_h \sin(x') e^{-t'} & \text{Impulsive} \\ a_h (\sin(x') + \cos(t')) & \text{Periodic} \\ a_h (x' + t') & \text{Linear} \end{cases} \quad (8)$$

409

where a_h is the amplitude of the source function (latter described), ω_i is the circular frequency ($\omega_i = 2 \pi f_i$), ϕ_i is a random phase between 0 and 2π , n is the number of summed simple harmonic components (here $n = 1500$).

Eq. (8) is expressed by four different types to individuate the characteristics of complicated ruptures, with a sine/cosine/exponential function that can represent the trend in time t' and space x' , because the accelerations of the source are unknown. In this sense, Eq. (8) defines a seismic source in both deterministic and probabilistic form. It is important to note that, in this way, if there is consistency with the motion of a random energy propagation, there may not be consistency with the rupture.

3.2.3 Hypocentre with punctual mass

Eq. (7) does not represent a physical quantity; therefore, it is necessary to introduce it in Eq. (8). As shown in literature [11], the source function can be correlated by the Lamé constant (or shear modulus) μ , which is related to the seismic moment by $M_0 = \mu \times A \times \bar{u}$, where A is the rupture area and $\bar{u}$ is the average displacement [3,13,72].

Also, in [11], Eq. (6) is expressed as the product of the EGF times an a-dimensional amplitude of M_0 , obtaining a EGF with the same units of $u(x, t)$. In an equivalent way, here it is introduced a hypocentre with an idealized punctual mass.

A new parameter is introduced in Eq. (8) in order to provide to Eq. (6) a physical quantity in terms of accelerations. From M_0 , it is obtained an equivalent relationship $M_0 = a_h \times M_\mu \times \bar{u}$, where a_h is the acceleration at hypocentre and M_μ is called “supermassive hypocentre”, expressed in kg. In this sense M_0 continues to be expressed as a force times a displacement, i.e. work.

The concept that allows to obtain this equivalent relationship is that the shear modulus μ , calculated as a shear force divided by the area on which the force acts, is calculated as a mass times acceleration. The accumulations of static stresses released by faulting (i.e. static stresses drop) have been idealized as an inertial force along a infinity fault line $\{L \equiv x' | x'(-\infty, \infty)\}$. The correlation, at mathematical level, between M_w and a mass has been already introduced in other studies [20,70].

Also, in his model, the fault is considered as linear. Therefore, $x' \in \Omega$ in Eq. (5) becomes an infinity line $-\infty < x' < \infty$, as shown in Eq. (6). The solution of Eq. (6) demands this infinity range, which could be justified by the fact that the considered M_0 are very large (see Table 6) and therefore the source dimensions are also very large. Moreover, the relationship between M_0 and x' is quasi-linear and tends to infinity as shown in literature [11,29,71].

Therefore, the acceleration a_h can be expressed as $a_h = M_0/(M_\mu \times \bar{u}) \approx M_0/M_\mu$ because both M_0 and M_μ have a very large magnitude (e.g. $\sim 10^{20}$) with respect to $\bar{u}$, which has a magnitude of meters. The objective is to estimate a unique parameter M_μ and a_h knowing PGA and M_0 . This is possible through the plotting of the Eq. (6) from hypocentre to site. In this way, two constant values are used like the approach shown in literature [27].

The model described in Fig. 8(a) is valid under the following hypotheses.

1. Epicentre and site points must be placed inside of a unique ZS so that all parameters retrieved from seismogenic zones are valid.
2. Hypocentre point must be at a depth $\Delta < 30$ km because ZS are calculated up to this depth. In this way, the probability $P[M_w > \mu_{w,i}]$ at the surface is the same at any point $P[M_w > \mu_{w,i}]$ at the wave path.
3. The source geometry must be modelled as linear. In this way Eq. (2) and Eq. (6) are valid.
4. Data of an earthquake registration must be taken from a station at a studied ZS. Both methods are correlated by M_w , which is retrieved from ZS and database, and then it is inserted in EGF.

479 Figure 8. New model for PSHA + EGF (a); vectors and tensors at seismic source and ground
 480 motion (b).

481

482 4 Results and discussions

483 4.1 Return periods by PSHA

484

485 As abovementioned, a ZS is characterized by seismic parameters (a-value, b-value, λ_c), which
 486 are obtained from a group of events that are homogeneous and independents of each other. This
 487 indicates that for the same ZS is possible to establish a unique period, T_e , in which these seismic
 488 parameters are maintained.

489

490 The hypothesis is that the seismogenic context for each ZS will be reasonably the same since
 491 the tectonic phenomena change during very long periods. However, the seismic parameters can
 492 suffer little variations because they are very sensible to the amount of data in the database. In
 493 this sense, there is a proposed a unique return period T_e consistent to the real sequence of events
 494 accounting for the seismogenic parameters.

495

496 The idea is not to eliminate the concept of the return period but to separate it from the
 497 calculation of acceleration, as a safety factor, given that, nowadays, specific studies that provide
 498 more reliable inputs are available. This aspect questions the use of extremely large return

periods, $T_r > 1000$ years, to increase seismic acceleration. Therefore, in this sense, via this methodology, the third problem described in introduction could be overcome.

Fig. 9 shows the results in a graphic M_w vs. year for three seismogenic zones (i.e. ZS 7, ZS 9, ZS 10). The dashed line represents the moving average of the events. The return period T_e refers to the maximum return period for which the characteristics of the seismicity maintains constant, whereas the return period $T_{\mu w}$ (interval of the vertical lines) is calculated by Eq. (4).

534 Figure 9. M_w vs. year and return periods for the ZS 9 (a), ZS 10 (b), ZS 7 (c).

In Fig. 9(a) there are 107 events in a period 1344-2002 years with a mean value $\mu_w = 4.3$. It is possible to see that in a period 1760-2002 years the sequence of the events is more consistent to the calculated $T_{\mu w}$ (in this period the moving average, the dashed line, oscillates more).

$T_{\mu w}$ is assumed as valid for all period. This because, as known, very old events are not recorded. However, geophysicists that have defined this seismogenic zone have considered these events as valid events that define the ZS 9. These considerations are also valid for Fig. 9(b) and Fig. 9(c).

Under these considerations, if $T_{\mu w} \leq T_r \leq T_e$, it is possible to assume T_r , provided by literature ($T_r = 475$ years), for any type of structures, because this period is rightly framed in a same seismogenic context. If this range is not verified, a $T_r \geq 475$ year loses meaning.

In this way, the importance factor is $\gamma_I = 1.0$. It is defined as $\gamma_I \approx (T_r/T_L)^{-1/k}$, where T_L is the return period of a requirement specific level, k is a factor that depend on the seismicity, which is generally of the order of 3.0, like the a -value (see Table 4) [8,50].

Table 7 resumes the results. It is possible to conclude that for these three seismogenic zones a T_r that should be used for all type of structures, independently of their importance, is 475 years.

Table 7. Summary of results.

Event	ZS	μ_w	$T_{\mu w}$ (year)	T_e (year)	$T_{r,max}$ (year)	
Évora, 2018	10	4.3	7.56	155.0	475.0 ^a	
Leiria, 1999	7	4.3	41.42	594.0		
Lisbon, 2000	9	4.3	14.64	658.0		
Lisbon, 2017						

^a It represents the maximum T_r that could be adopted for designing of any type of structure placed in a specific ZS.

The results for Lisbon are consistent with the literature [64] where the probability of exceedance of 475 years is less than 1% for the magnitude 3.5-6.5. This confirms that using a period longer than 475 years overestimates the seismic input.

It is important to note that the offshore seismicity has not been considered, which affects the seismicity of these studied places as shown in literature [64]. This is because by considering the offshore zones, e.g. ZS 50, where the great 1755 Lisbon earthquake was generated, the seismicity increases as commented also in [67]. The idea in this work is not to consider very distant zones to estimate seismic inputs because (i) there are no attenuation equations for Portugal that can well calibrate the results at these distances (see Table 1); (ii) the adopted model follows Fig. 8(a)

These results should separate the PGA of γ_I , which relates to the consequences of a structural failure. Buildings are classified in classes, depending on the consequences of collapse for human life, public safety, civil protection and thus social and economic consequences in the post-earthquake period [7,8].

The logic to divide the performance requirements in no-collapse and damage is fundamental, but it should not motivate an increase in seismic input. It should be associated to the completeness of modelling, deepening of seismic analyses (object of this study), design and detailing of primary and secondary elements and connections.

An overestimation of γ_I leads to an overdesigning of, for instance, small structures considered as important, because the design inertial force can reach very high values. Moreover, in many cases, the lack of attention for designing of small/medium structures makes using a high input value quickly solve the security problem. For this reason, it is useful to separate the acceleration from γ_I , but focusing more on the modelling and detailing.

4.2 Ground motions by EGFs

Fig. 10 shows the source function $f(x', t')$ defined by Eq. (8) in 2D and 3D for four cases: random, impulsive, periodic, linear. The 2D trend (f vs. t') is a transversal section of the 3D trend at $x' = 0$, except for the impulsive function that is calculated at $x' = 1.5$ m. Used data refer to the Lisbon 2000 event.

2D (at $x' = 0$ m for random, periodic, linear;
at $x' = 1.5$ m for impulsive)

Random source function (a)

Impulsive source function (b)

Periodic source function (c)

Linear source function (d)

600 Figure 10. Source function (see Eq. (8)) expressed by a random (a), impulsive (b), periodic (c),
601 linear (d) function in 2D/3D. Used data refer to Lisbon 2000 event. Horizontal dashed line
602 represents the PGA value (i.e. 0.057 m/s^2).
603

The source function, expressed by four types of functions, represent an artificial acceleration [26] of the soil at hypocentre. These functions are plotted in the significant duration T_s , i.e. $0 \leq t' \leq T_s$ (see Table 6), whereas the spatial variable x' is plotted between $10 \leq x' \leq 10$ m.

In 3D view it is possible to see that the released energy comes from a line where the acceleration assumes a value of $f \neq 0$ at $t' = 0$.

Figure 11 shows the results for the Lisbon 2000 event in terms of displacements of the ground motion computed by using Eq. (6), then, by deriving Eq. (6) in the time t , velocities and accelerations are obtained.

The impulsive source function is used as reference, i.e. the parameters M_μ and a_h are calibrated considering $(\ddot{u}(x,t) - \text{PGA}) \approx 0$ under an impulsive source function. Because an impulsive function is consistent to the physical process described in Eq. (6). Therefore, the amplitude a_h is calculated iteratively from registered PGA and M_0 for each event. In function of this calibration, other values of $\ddot{u}(x,t)$ are estimated. Thus, it is possible to note what source function well estimates the $\ddot{u}(x,t)$.

Figure 11. Solutions in terms of displacements (a), velocities (b), accelerations (c) of the ground motion for 2000 Lisbon earthquake.

During the integrations, the values of the ground displacements assume ever larger values due to the strong influence of the Green's function g , expressed in Eq. (7), that assumes exponential values in function of the time t (see Fig. 7). This function is predominant with respect the source functions expressed by Eq. (8). In fact, in the velocities and accelerations of the ground, it is possible to see that the trend follows always the trend of the artificial accelerograms, because the influence of the Green's function is weaker.

Figs. 12-14 show the ground accelerations for the other three considered events.

Évora, 2018

Figure 12. Solutions in terms of accelerations of the ground motion for 2018 Évora earthquake.

Lisbon, 2017

645 Figure 13. Solutions in terms of accelerations of the ground motion for 2017 Lisbon earthquake.

646

Leiria, 1999

647 Figure 14. Solutions in terms of accelerations of the ground motion for 1999 Leiria earthquake.

648

649 Fig. 15 shows the relative error, for the four events, expressed in percentage (%) calculated as:

650 $(\text{calculated value} - \text{registered value})/\text{calculated value}$. The registered values are shown in Table

651 6. In this way it is possible to estimate the contributions of the different source functions for
652 PGD, PGV, PGA.
653

(d)

Figure 15. Relative error of each type of source for the 2000 Lisbon event (a), the 2018 Evora event (b), the 2017 Lisbon event (c), the 1999 Leiria event (d),

In Fig.15 it is possible to see that for the values of PGD and PGV it is difficult to obtain a good result due to the amplification already mentioned and shown in Fig. 7. In fact, this model is applicable to estimate the PGA because the amplitude a_h in Eq. (8) is introduced for this scope.

For the PGA, it is possible to see that the source function expressed by a random and periodic function provide good results. In particular, the periodic function provides the best results with a mean relative error for PGA of 21%. Due to the stochastic nature of the random function, in some case the results are good (Fig. 15(a)) whereas in other cases they are not (Fig. 15(b)-(c)-(d)). By using a linear function, the PGA values are poor.

Table 8 shows the values of the parameters introduced in this analysis, i.e. a_h and M_μ , which are correlated by $a_h \approx M_0/M_\mu$.

Table 8. Values of a_h and M_μ .

	Évora, 2018	Leiria, 1999	Lisbon, 2000	Lisbon, 2017
a_h (m/s ²)	0.0124	0.276	0.0627	0.0021
M_μ (kg)	1.20×10^{23}	5.03×10^{23}	2.07×10^{23}	1.81×10^{26}

The station location that registers the signals can be very distance to the epicentre. In many cases, this distance is larger than the radius of the ZS, and, therefore, the relation between the parameters of the PSHA and the parameters of the seismic source are not compatible (see Fig. 4). However, this problem also exists for the traditional PSHA by using attenuation equations.

In fact, when more ZSs are considered to develop a unique analysis, the mean parameters of ZSs are used. In this way, the mean of b-values for several ZSs are calculated despite the fact that the adopted attenuation equation is calibrated for a unique homogenous mechanism fault, i.e. for a unique ZS [30].

The model described in Fig. 8, must be applied in an area that corresponds to a unique ZS. Therefore, as shown in Fig. 4, rigorously only where the results of the 2000 Lisbon earthquake (Fig. 11) would be valid. However, mathematically, the method would continue to be also valid for other events.

5 Conclusions

This paper combines the PSHA with EGFs through M_w describing the source function via random, impulsive, periodic, linear function. Some parameters of ZSs for Portugal and specific return periods have been estimated.

The main conclusions are:

1. A comparison between the parameters of existing seismogenic zones (Share, Ersta, EC8, ZESIS) and other parameters estimated in this paper has been carried out. In this sense, it has been demonstrated that the epistemic uncertainties correlated to the models are still very changeable. Table 3 shows the difference of the main parameters for PSHA (i.e. b-value), which can contribute to reduce the gap of the various models.

2. An overestimation of γ_I leads to an overdesigning of, for instance, small structures considered as important, because the design inertial force can reach very high values with a small increasing of γ_I . In many cases, for small/medium structures, the use of a high input value “resolves” the security problem neglecting an attention for designing. For this reason, it is useful to separate the PGA from γ_I as shown in Table 7. For important small structures it will be essential focusing more on the modelling and detailing.

3. A new analytical approach to correlate PSHA with EGFs has been proposed. The key parameter for this correlation is M_w , which is estimated by PSHA and introduced in EGFs by

M_0 through relationship $a_h \approx M_0/M_\mu$. Results are shown in Table 8. The model is valid under conditions shown in the Fig. 8.

4. Four types of source functions have been studied: random, impulsive, periodic, linear. This because a priori the source accelerations are not known. Results show that the periodic function render better results. The relative error between the calculated and registered value is 12-36%. However, for PGA, a source function described by random function has a good calibration.

Conflict of interest

None.

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Annex

The inhomogeneous (i.e. $\neq 0$) wave equations in one dimension for a function $w(x, t)$ is, for $-\infty < x < \infty$, $t > 0$, given by (the process is retrieved from [18] and adapted to this study):

$$\frac{\partial^2 w(x,t)}{\partial x^2} - \frac{1}{\beta_s^2} \frac{\partial^2 w(x,t)}{\partial t^2} = h(x, t) \quad (A1)$$

for some given function $h(x, t)$.

The Green's function $g(x, t; x', t')$, by the Dirac delta function δ [17], associated with Eq. (A1) satisfies

$$\frac{\partial^2 g(x, t; x', t')}{\partial x^2} - \frac{1}{\beta_s^2} \frac{\partial^2 g(x, t; x', t')}{\partial t^2} = \delta(x - x') \delta(t - t') \quad (\text{A2}).$$

743

744 By using a Fourier's transform, it is obtained:

745

$$\frac{1}{\beta_s^2} \frac{\partial^2 G(x, t; x', t')}{\partial t^2} + x^2 G(x, t; x', t') = \delta(t - t') e^{ixx'} \quad (\text{A3}).$$

747

748 Let $G(x, t; x', t') = \exp(ixx') r(x, t)$, a function $r(x, t)$,

749

$$\frac{1}{\beta_s^2} \frac{\partial^2 r(x, t)}{\partial t^2} + x^2 r(x, t) = \delta(t - t') \quad (\text{A4})$$

751

752 therefore

753

$$\frac{1}{\beta_s^2} \frac{\partial^2 r(x, t)}{\partial (t - t')^2} = -x^2 r(x, t) \quad (\text{A5}),$$

755

756 which has solutions $r(x, t) = A(t) \sin [x(t - t')]$, with $A(t) = \int \delta(t - t')/x \, dt$, is an amplitude of sine
757 function.

758 By using the fact that $\int \delta(t - t') dt = \Theta(t - t')$, $r(x, t)$ is

759

$$r(x, t) = \frac{\sin[x(t - t')] \Theta(t - t')}{x} \quad (\text{A6})$$

761

762 therefore, considering the equivalence between Eq. (A3) and Eq. (A4),

763

$$G(x, t; x', t') = \frac{e^{ixx'} \sin[x(t - t')] \Theta(t - t')}{x} \quad (\text{A7}).$$

765

766 Thus, it is shown that the Fourier's transform in x of the Green's function, $G(x, t; x', t') = F(g(x,$
767 $t; x', t'))$, is given by Eq. (A7),

768

769 Finally, by taking the inverse of Fourier's transform

770

$$g(x, t; x', t') = F^{-1}[G(x, t; x', t')] = \frac{1}{2\pi} \int_{-\infty}^{\infty} G(x, t; x', t') e^{-ix^2} dx = \int_{-\infty}^{\infty} \frac{\theta(t-t') \sin[x(t-t')] e^{ix(x'-x)}}{2\pi x} dx \quad (A8)$$

773

774 and by using two general identities (i) $2\sin(\alpha)(\cos(\beta) + \sin(\beta)) = \sin(\alpha - \beta) + \sin(\alpha + \beta) + \cos(\alpha$
 775 $- \beta) - \cos(\alpha + \beta)$ and (ii) $e^{i\alpha} = \cos(\alpha) + i \sin(\alpha)$, it is obtained

776

$$g(x, t; x', t') = \frac{\theta(t-t')}{4\pi} \int_{-\infty}^{\infty} \left(\frac{\sin[x(t-t'+x'-x)]}{x} + \frac{\sin[x(t-t'-x'+x)]}{x} + i \frac{\cos[x(t-t'+x'-x)]}{x} + i \frac{\cos[x(t-t'-x'+x)]}{x} \right) dx \quad (A9).$$

779

780 Neglecting the imaginary part, knowing that $\int_{-\infty}^{\infty} \frac{\sin(\alpha)}{\alpha} d\alpha = \pi$ and introducing the sign
 781 function as $\text{sgn}(\alpha) = -1, 0, 1$ for $\alpha < 0, \alpha = 0, \alpha > 0$, respectively, Eq. (A9) is:

782

$$g(x, t; x', t') = \frac{\theta(t-t')}{4\pi} \pi (\text{sgn}(t - t' + x' - x) + \text{sgn}(t - t' - x' + x)) \quad (A10)$$

784

785 that, considering $\text{sgn}(\alpha) \approx 2 \Theta(\alpha)$, can be written as

786

$$g(x, t; x', t') = -\frac{1}{2} \theta[(-t' + t) - |-x' + x|] \quad (A11)$$

788

789 that is Eq. (7).

790

791 Note that Eq. (7) has a similar form with respect to the general solution of Eq. (A1) with $h(x, t)$
 792 $= 0, \beta_s = 1$ and unbounded condition $B = 0$, that is $w(x, t) = c_1(t - x) + c_2(t + x)$, where c_1 and
 793 c_2 are two arbitrary differential equations.

794

795 References

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