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A STOCHASTIC FINITE – FAULT MODELING FOR THE 1755 LISBON EARTHQUAKE

Alexandra CARVALHO[1], Alfredo CAMPOS COSTA[2] and Carlos Sousa OLIVEIRA[3]

SUMMARY

This work presents a non-stationary stochastic seismological model, based on random vibration theory. The model is applied to the 1755 Lisbon earthquake, being a tentative of reproducing the input motion of this severe earthquake.

Five possible interpretations of the fault source mechanism, recently proposed by several authors for the 1755 Lisbon earthquake, are analyzed. Three interpretations are based on seismic surveys and two from a suggestion based on induced stress changes.

In order to test the feasibility of the different proposed fault source mechanisms to reproduce the historical intensities of the earthquake, ground motion maps were obtained at bedrock level and the degree of the interrelationship between some seismic parameters and the intensities of the earthquake are described by a correlation analysis.

INTRODUCTION

Portugal is an area typically of moderate seismicity. The occurrence of the events appears in a random fashion in both space and time, with rare occurrences of large earthquakes.

The determination of a regional response spectrum requires the analysis of a large number of strong motion accelerograms representative of the whole range of source, path and site conditions.

In Portugal, being located at a moderate/low seismicity intraplate area, insufficient accelerograms have been recorded to satisfactory undertake any regional empirical study. The number of accelerograms is not only small but also refers to low-magnitude earthquakes located in only some parts of its entire seismic area. For that reason, most prediction techniques of ground motion in Portugal have been based on international empirical laws and not on regional data to quantify the characteristics of ground motions.

[1]PhD Grant Holder, Laboratório Nacional de Engenharia Civil, Lisbon, Portugal. Email: xana.carvalho@lnec.pt
[2] Senior research, Laboratório Nacional de Engenharia Civil, Lisbon, Portugal. Email: alf@lnec.pt
[3] Full Professor, Instituto Superior Técnico, Lisbon, Portugal. Email: csoliv@civil.ist.utl.pt

However, differences in the regional geology can led to variations in ground motions characteristics and the use of empirical laws of other regions is questionable and may not be appropriate for Portugal.

As prediction cannot be based on empirical analyses, theoretical models must be used as the basis for the predictions of strong motion in Portugal. The development of stochastic based ground motion synthesis associated to a seismological finite-fault modeling is, probably, the only approach that can be used for realistic representation of future large magnitude earthquakes occurring in Portugal.

NON-STATIONARY STOCHASTIC FINITE FAULT SIMULATION METHOD

The total radiation at a specific site, defined by the Fourier Amplitude Acceleration spectrum is a result of contributions from earthquake source, path and site and is defined by (eg.Boore [1,2])

$$A(\omega,R) = \omega^2 \cdot C \cdot S(\omega) \cdot G(R) \cdot An(\omega,R) \cdot P(\omega) \cdot V(\omega) \tag{1}$$

where

- C is the scaling factor

$$C = \frac{\Re \cdot V \cdot FS}{4 \cdot \pi \cdot \rho \cdot \beta^3} \tag{2}$$

$\Re$ is the wave radiation factor ($\Re$ = 0.55 on average for shear waves, e.g. Boore [2], V is the factor partitioning energy in two horizontal components (V = 0.701), FS is the free surface amplification factor (FS = 2), and ρ and β are the density of the rock at the depth of rupture and the shear wave velocity of the rock, respectively, in the vicinity of the source.

- $S(\omega)$ is the displacement source spectrum given by Brune's omega square model [Brune [3,4]] and is represented by

$$S(\omega) = \frac{M_o}{1 + \left(\omega/\omega_c\right)^2} \tag{3}$$

where M_o is the seismic moment, $\omega=2\pi f$ and $\omega_c=2\pi f_c$ being f_c the source corner frequency $f_c = 0.49 \cdot \beta \cdot \left(\Delta\sigma/M_o\right)^{1/3}$ with all the parameters expressed in consistent SI units and $\Delta\sigma$ is the stress drop or stress parameter.

- $G(R)$ is a geometric attenuation factor, which reduces the entire spectrum with distance from the source without altering its shape.

- $An(\omega,R)$ is the anelastic whole path attenuation factor [Boore [1]]

$$An(\omega,R) = \exp\left[\frac{-\omega \cdot R}{2 \cdot Q \cdot \beta}\right] \tag{4}$$

where Q is the wave transmission quality factor which is defined by the expression $Q(f) = Q_0 \cdot f^{\nu}$ and Q_0 and ν are the regional dependent factor for f =1 Hz and exponent respectively. This factor will alter spectrum shape by reducing high frequencies more rapidly with distance than lower frequencies.

- $P(\omega)$ is the upper crust attenuation factor, a high-cut filter, that accounts for the observation that acceleration spectra often show a sharp decrease with increasing frequency, above some cutoff frequency, $\omega_{\max}$, obtained as (eg. Boore [2])

$$P(\omega) = \left[1 + \left(\frac{\omega}{\omega_{\max}} \right)^8 \right]^{-1/2} \tag{5}$$

- $V(\omega)$ is the upper crust amplification factor that accounts for the increase in wave amplitude as seismic energy travel through lower – velocity crustal materials from the source to the surface and depends on average crustal and near surface shear-wave velocity and density.

The final input parameter to take into account to perform a stochastic simulation is the duration of the ground motion, Ts, which we assume it has two components: the source duration, taken as the inverse of the corner frequency, and a path dependent duration, due to multi-pathing and scattering effects [Beresnev [5]].

The one-sided power spectral density function (PSDF) of acceleration can be estimated from the Fourier amplitude spectrum, $A(\omega,R)$ (equation 1) and the source duration, Ts, in such a way that [eg. Boore [6]]

$$Sa(\omega) = \frac{1}{\pi} \frac{|A(\omega, R)|^2}{Ts} \tag{6}$$

The PSDF of the response of the oscillator with a circular frequency ω_n and a damping ratio ζ to a ground motion characterized by PSDF $Sa(\omega)$ is, assuming a stationary process, calculated as:

$$S_x(\omega, \omega_n, \xi) = Sa(\omega) \left| H_x(\omega, \omega_n, \zeta) \right|^2 \tag{7}$$

in which $H_x(\omega, \omega_n, \zeta)$ is the complex frequency transfer function of the oscillator for relative displacement to an input base acceleration.

The stationary response moments of order k is written as

$$\lambda_k(\omega, \omega_n, \zeta) = \int_0^{\infty} \omega^k S_x(\omega, \omega_n, \zeta) d\omega \tag{8}$$

To cope with the non stationary of the intensity of the response of the oscillator, a intensity modulating response function in time, θ, is specified directly in a way that the evolutionary response moment is obtained by the modulating function and the stationary moment as

$$\lambda_k(t, \omega, \omega_n, \zeta) = \theta^2(t, \omega_n, \zeta) \cdot \lambda_k(\omega, \omega_n, \zeta) \tag{9}$$

in which the response modulating function is obviously dependent of frequency and damping of the one degree of freedom system and can be found in Duarte [7]. The context and simplifications that are implicit when using this response modulating function are pointed out in Campos Costa [8].

The effects of a large finite source, including rupture propagation, directivity and source receiver geometry can profoundly influence the amplitudes, frequency content and duration of ground motion.

A common approach to modelling these effects is to subdivide the fault into smaller parts, each of which is then treated as a point source (Figure 1). The ground motion at an observation point is obtained by summing the contributions over all sub faults.

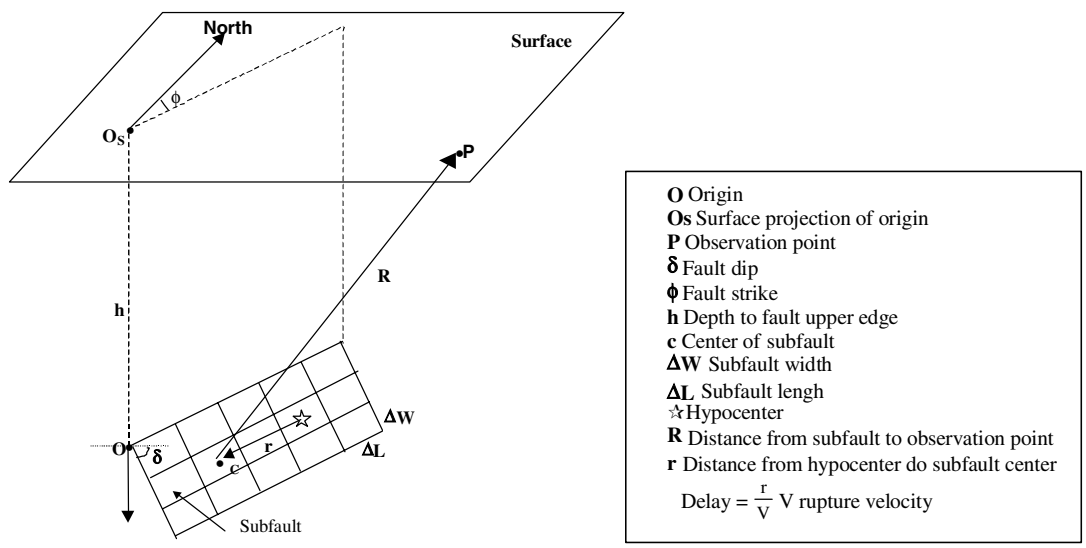

Figure 1. Finite –fault geometry (adopted from Beresnev [9])

The number of sub-sources added in the simulation is constrained by the similarity law of earthquakes. The parameters are determined to be consistent with the scaling relations between seismic moment and fault parameters such as fault length and width.

Considering two events with different sizes, which occurred within the same source region, the similarity relations between those source parameters are [Irikura, 10]:

$$\frac{L}{L_e} = \frac{W}{W_e} = \left(\frac{M_o}{M_{oe}}\right)^{1/3} = n \qquad (10)$$

where L is the length and W is the width of the rectangular seismic source and M_0 is the seismic moment. The parameters without subscript e are for mainshock and those with subscript e, for small events. These relations are approximated by an integer n and the mainshock fault plane is divided into $n \times n$ elements.

An element triggers when the rupture reaches its centre. The contributions from all elements are lagged and summed at the receiver. The time delay for an element is given by the time required for the rupture to reach the element, plus the time for shear wave propagation from the element to the receiver.

For a finite source, subdivided into *N* sub-faults, and considering that stochastic process associated to all the N subfaults are independent, the final evolutionary finite–fault response moment, $\lambda_k{}^T$, can be estimated as the sum of all subfault response moments, meaning that:

$$\lambda_k{}^T\left(t,\omega,\omega_n,\zeta\right)=\sum_{j=1}^{N}\theta_j^2\left(t,\omega_n,\zeta\right)\cdot\lambda_{k\ j}\left(\omega,\omega_n,\zeta\right) \tag{11}$$

Considering the extreme values statistics and taking T as the maximum value for which the zeroth moment, $\lambda_0{}^T$ is maximum, the non-stationary response spectrum that synthesizes the integration of all the delayed ruptures over the fault is

$$RS\left(T,\omega,\omega_n,\zeta\right)=\left(\sqrt{2\cdot\ln(2\cdot fe\cdot T)}+\frac{0.577216}{\sqrt{2\cdot\ln(2\cdot fe\cdot T)}}\right)\cdot\sqrt{\lambda_0{}^T\left(T,\omega,\omega_n,\zeta\right)} \tag{12}$$

where, following Vanmarcke [11]

$$fe=\begin{cases}(1.63\cdot\delta^{0.45}-0.38)\cdot fo & \delta<0.69\\ fo & \delta>0.69\end{cases} \tag{13}$$

$$fo=\frac{1}{2\pi}\left(\frac{\lambda_2{}^T\left(T,\omega,\omega_n,\zeta\right)}{\lambda_0{}^T\left(T,\omega,\omega_n,\zeta\right)}\right)^{1/2} \tag{14}$$

being δ the bandwidth parameter defined as

$$\delta=\left(1-\frac{\lambda_1{}^T\left(T,\omega,\omega_n,\zeta\right)^2}{\lambda_0{}^T\left(T,\omega,\omega_n,\zeta\right)\cdot\lambda_2{}^T\left(T,\omega,\omega_n,\zeta\right)}\right)^{1/2} \tag{15}$$

Once the non-stationary response spectra has been achieved, and equivalent stationary PSDF can be iteratively estimated, following the classical theory of stationary random process. This approach was adopted in an automatic seismic loss estimate methodology that was developed at LNEC, integrated on a Geographic Information System (see an accompanying paper, Sousa [12]).

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AN APPLICATION TO THE 1755 LISBON EARTHQUAKE

State of the art: Fault source mechanisms proposed

The 1755.11.01 earthquake, known as the 1755 Lisbon earthquake, generated the largest known tsunami in SW Europe and its magnitude has been estimated as Mw= 8.5 – 8.9 by several authors [e.g. Machado [13], Abe [14]; Moreira [15]]. The exact location remains controversial, even though the earthquake's epicentre is know to have been offshore.

The several isoseismal maps published (eg. Figure 2, left) led to the conclusion that the source location of this event was in the vicinity of Gorringe Bank [Martinez Solares [16], Levret [17]], the most prominent

high situated in the eastern end of Azores-Gilbratar ridge (GB, Figure 2). This location was (strengthened) further supported by the occurrence of a tsunamigenic earthquake on 1969.02.28.

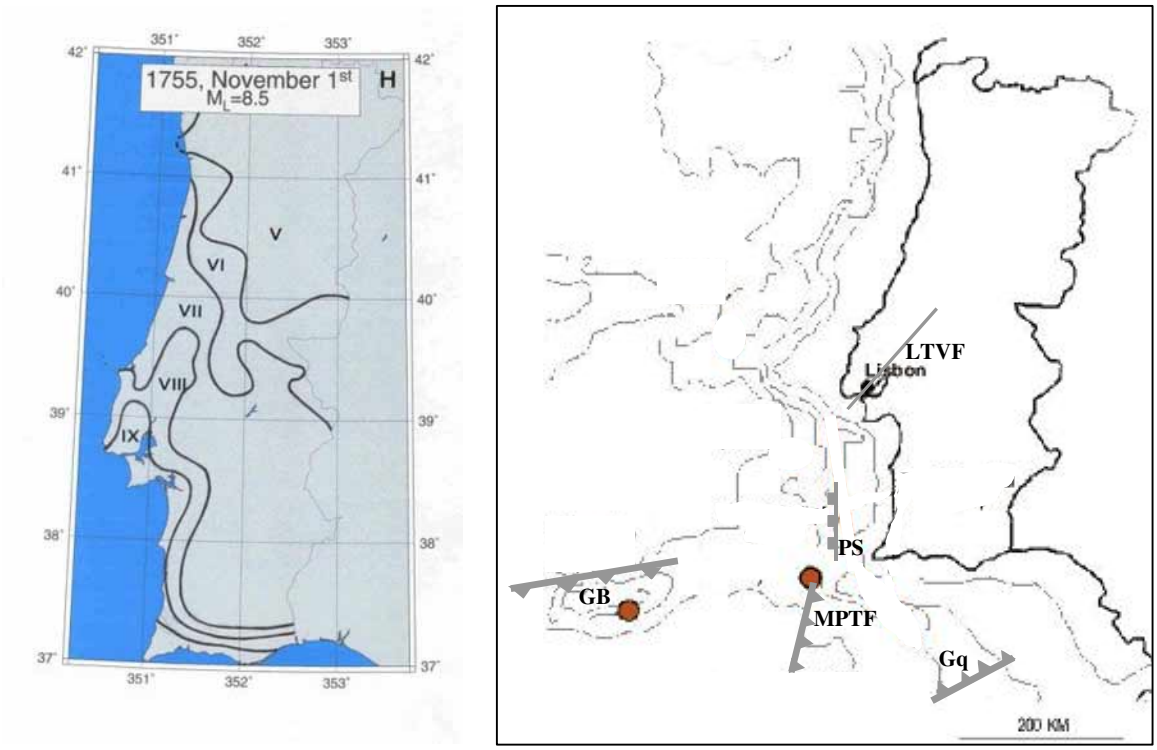

Figure 2. Left: Isoseismal of the 1755 earthquake from Moreira [15]. Right: Structural features: **GB**- Gorringe Bank. Thrust fault geometry used by Johnston [18]; **MPTF**- Marques Pombal Thrust Fault; **Gq** –Guadalquivir Bank; **PS** – Pereira de Sousa Fault; **LTVF** – Lower Tagus Valley Fault. Red circles show epicentral locations proposed by different authors and used in this study, for the Lisbon 1755 earthquake. Red circle in GB: Coordinates 36.45ºN-11.25ºW, proposed by Machado [13]; Red circle in MPTF: coordinates 37ºN-10ºW, proposed firstly by Rodriguez [19].

However, a regional multi-channel seismic reflection survey performed in 1992 to investigate the stratigraphic and tectonic features of the eastern end of the Azores-Gibraltar line, recorded several lines across Gorringe Ridge that do not show evidence of recent major uplift showing that most of the up-dip movement was confined to before early Pliocene times [Sartori [20]].

Baptista [21] performed a hydrodynamic modelling of the 1755 tsunami. Results from a backward ray tracing simulations suggest a tsunami source located quite close to the Portuguese coast, on its continental shelf, extending between the latitude of Lisbon to the Guadalquivir fault, south of Iberia.

In order to precisely locate the 1755 seismogenic source, in 1998 the area between the Gorringe Bank and the Cape St. Vicente has been surveyed within the framework of the European BIGSETS projects (Big Sources of Earthquake and Tsunami in SW Iberia). One of the main results [Zitellini [22]] was the characterization of the active tectonic structure located offshore Cape St. Vicente named as Marques Pombal thrust fault (MPTF, Figure 2) which, accordingly to the authors, could be the generator of the 1755 Lisbon earthquake, near the epicentre location 37ºN 10ºW obtained by Rodriguez [19] (red circle, near MPTF, Figure 2).

Terrinha [23] pointed out that additional rupture areas have to be associated with the MPTF system to generate such a destructive earthquake and that the 65 *km* long Pereira de Sousa Fault (PS, Figure 2) located along the Portuguese margin, to the north of MPTF, could constitute the northward prolongation of the MPTF (see figure 11 of Terrinha [23]). Like this, the total rupture area is enlarge from 7000 km^2 [Zitellini [22]] to 19000 km^2, which is capable to generate a Mw=8.6 magnitude earthquake. This localization is compatible with Baptista [21] numerical modeling.

Baptista [24], based on new MCS (multi-channel seismic reflections surveys) data, presented a new reappraisal of the 1755 source and proposed a possible composite source including the Marques de Pombal thrust fault and the Guadalquivir Bank (Gq, Figure 2), which, accordingly to authors, will act as a possible southeastward extension of the rupture area related to the 1755 event.

Vilanova [25] propose that, although the main shock was offshore, the resulting static stress changes induced the rupture of the Lower Tagus Valley (LTVF, Figure 2), near Lisbon. They favor this model, rather that site effects causing high intensities in the Lisbon area, because not only the highest intensities show a negative correlation to soft soil but also because this local rupture can explain other phenomena described in the eyewitness accounts like an internal tsunami in the Tagus River, ground deformation affecting the course of the Tagus River, the spatial pattern of damaging aftershocks, duration of the event and the number of shocks felt.

Model parameters

Using the stochastic finite fault method explained above, we have tested three different fault source geometries for the source of the 1755 earthquake that resulted from seismic survey and two fault source geometries based on a suggestion of induced stress changes.

For all geometries, fault segments were divided into smaller parts, accordingly to equation (10), each one considered as a point source. The slip distribution is randomized and could be zero in many sub-faults. To achieve the target moment, the elementary faults with non zero slip are allowed to trigger more than once, in such a way the total number of point sources summed do not change.

For the first three models, the total fault were subdivided into 9×9 smaller part, each one considered as a point source and in all of them radial rupture was considered. It was adopted the coordinates 37ºN-10ºW for the initial point of the rupture.

Figure 3 presents the fault source geometries considered and table 1 shows the fault source parameters. The geometry named MPTF considers the proposal of Zitellini [22], the geometry MPTF-PS considers the proposal of Terrinha [23] and the model MPTF-Gq considers the new study of Baptista [24].

The last two models, consider besides the main shock, a second earthquake in Lower Tagus Valley Fault (LTVF) in which the LTVF is divided into 10 x 10 sub-faults. The first one, named here GB-LTVF (Figure 4), considers that the main shock was in Gorringe Bank fault, and for the modeling it was considered the geometry adopted by Johnston [18] and the epicenter of Machado [13] at 36.45ºN-11.25ºW. The second modeling, MPTF-LTVF (Figure 4), considers that the main shock was in Marques Pombal Thrust Fault. Table 2 summarizes the fault geometries parameters.

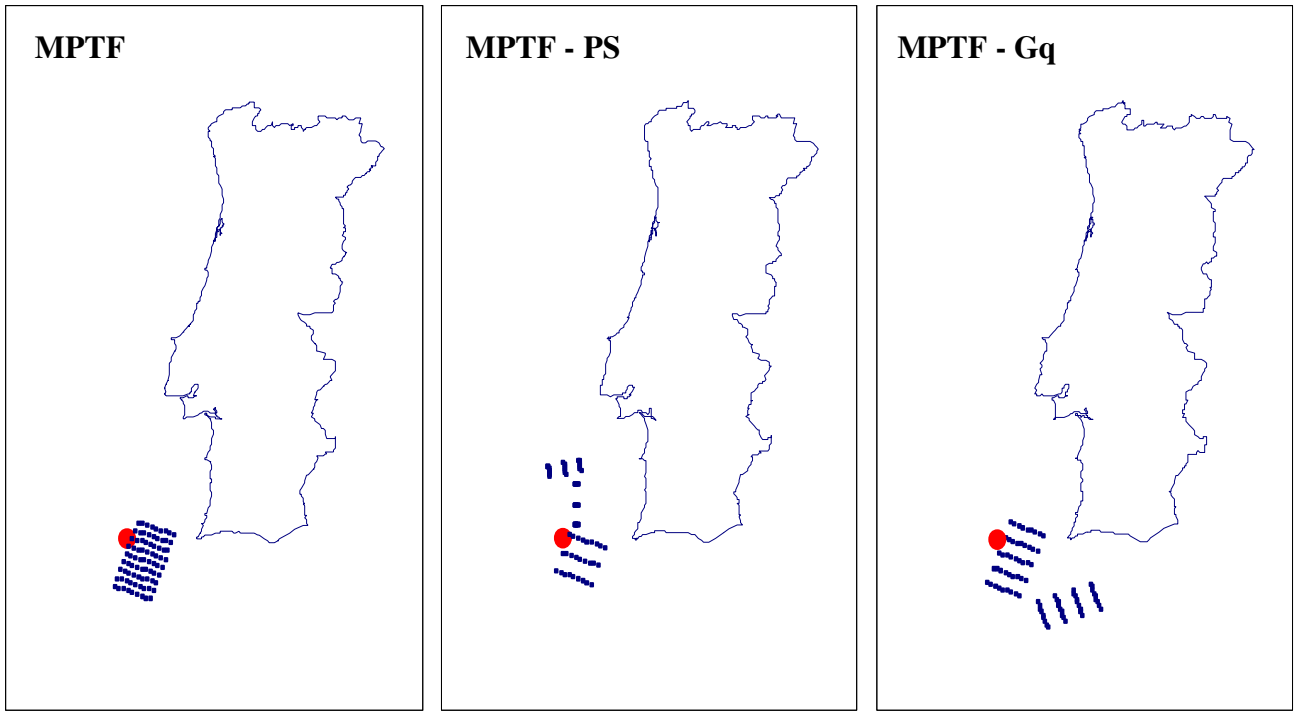

Figure 3. Surface projection of the three fault source geometries proposed by different authors after seismic surveys. The blue circles show the center of the sub-faults. Red circle shows localization 37ºN – 10ºW, corresponding to the accepted epicentral coordinates of the 1755 earthquake and considered as the initial point of rupture. Left: fault source geometry after Zitellini [22]; Middle: fault geometry after Terrinha [23]; Right: fault geometry after Baptista [24]

Table 1. Fault source parameters for the three fault source geometries proposed after seismic surveys, and represented in figure 3.

	MPTF	**MPTF – PS**	**MPTF – Gq**
Strike	N20E	N20E ; N-S	N21.7E ; N70E
Dip	24º	24º	24º ; 45º
L x W (km)	100 x 70	65 x 70 ; 65 x 6	105 x 55 ; 96 x 55

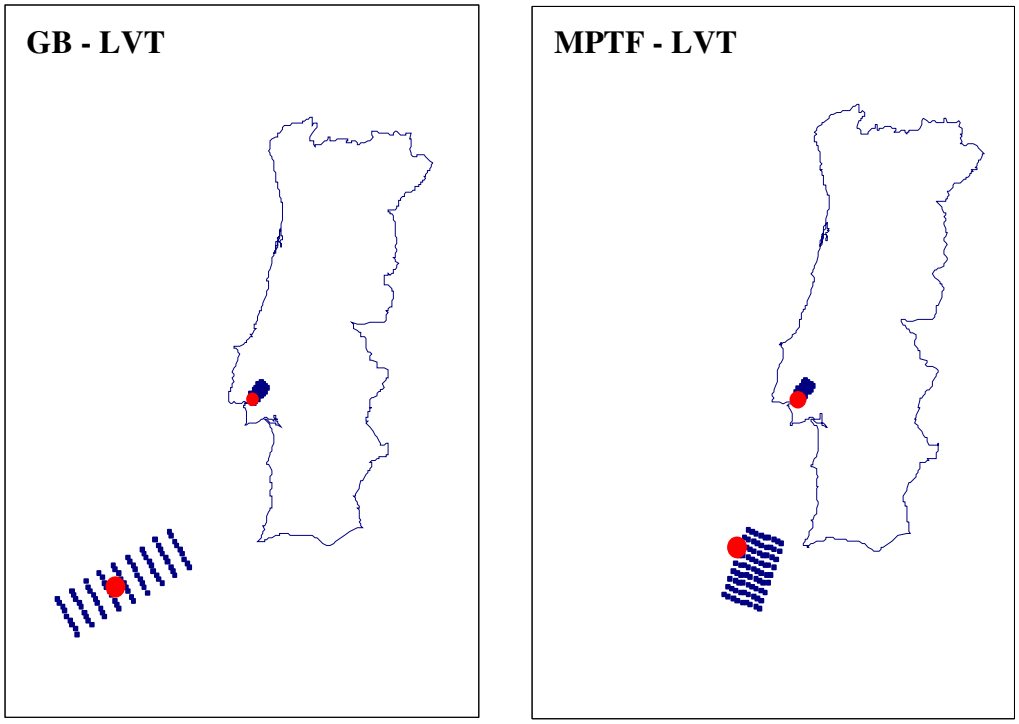

Figure 4. Surface projection of the two fault source geometries that consider two different shocks. The blue circles show the center of the sub-faults. Red circles show localization of epicentres. Left: fault source geometry after Vilanova [25], considering the main shock in the Gorringe Bank region, with the geometry adopted by Johnston [18] and the epicentral localization of Machado [13]; Right: fault source geometry after Vilanova [25], considering the main shock in the MPTF region. The authors decided the epicentral localization of the initial point of rupture in the LTVF.

Table 2. Fault source parameters for the two fault source geometries that consider besides the main shock, a second earthquake in LTVF, and represented in figure 4.

	GB - LTVF	**MPTF – LTVF**
Strike	N60E; N40E	N20E; N40E
Dip	40º; 55º	24º; 55º
L x W (km)	200 x 80; 36 x 25	100 x 60; 36 x 25

Table 3 summarizes all modeling parameters used, including source, path propagation and crustal effects that were described in the first pages of this work.

Table 3. Modeling parameters for the stochastic finite-fault model

Parameters	MPTF; MPTF-PS; MPTF-Gq	GB-LTV; MPTF-LTVF
Magnitude of main event	8.7	7.0
Elementary magnitude	6.5	5.0
Quality factor, Q(f)	$345*f^{0.7}$ [Pujades [26]]	
Geometric attenuation	1/R (R ≤ 70 km) $1/R^0$ (70 km < R ≤ 130 km) $1/R^{0.5}$ (R > 130 km)	
Distance-dependent duration	0.05 R	
Crustal amplification	1	
f_{max}	50 Hz	
Shear-wave velocity, β	3.5 km/sec	
Rupture velocity	2.5 km/sec	
Crustal density, ρ	2.8 g/cm^3	
Slip distribution	Random	
Stress drop, Δσ	120 *bars*	
Number of trials	3	

Results and discussion

For each fault geometry seismic action was computed at the bedrock level, namely the peak ground acceleration, PGA, the peak ground velocity, PGV, and the peak ground displacement, PGD. Figures 5 to 9 present those results.

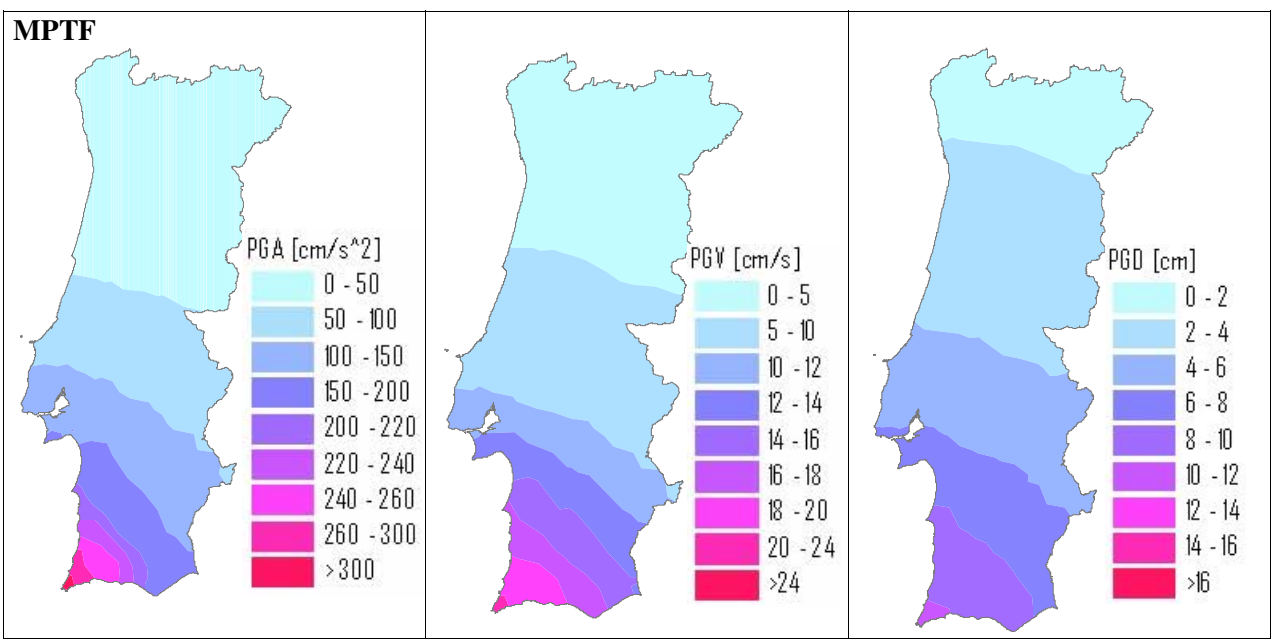

Figure 5. Peak ground acceleration, peak ground velocity and peak ground displacement at the bedrock level, for the MPTF fault source geometry.

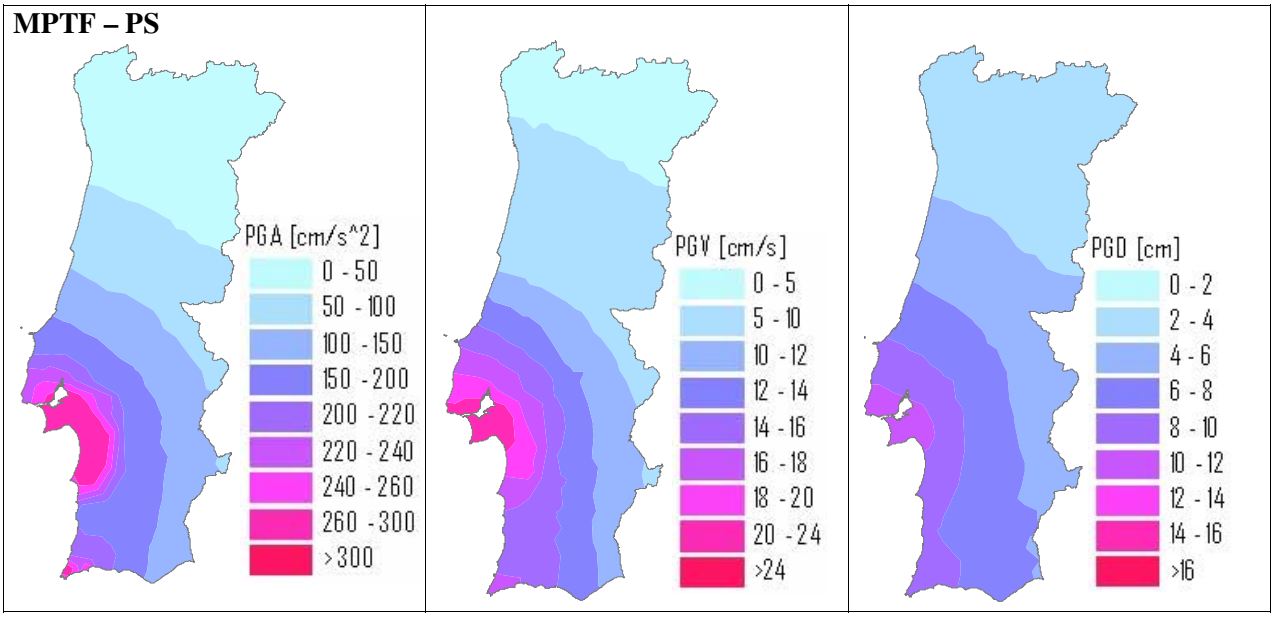

Figure 6. Peak ground acceleration, peak ground velocity and peak ground displacement at the bedrock level, for the MPTF-PS fault source geometry.

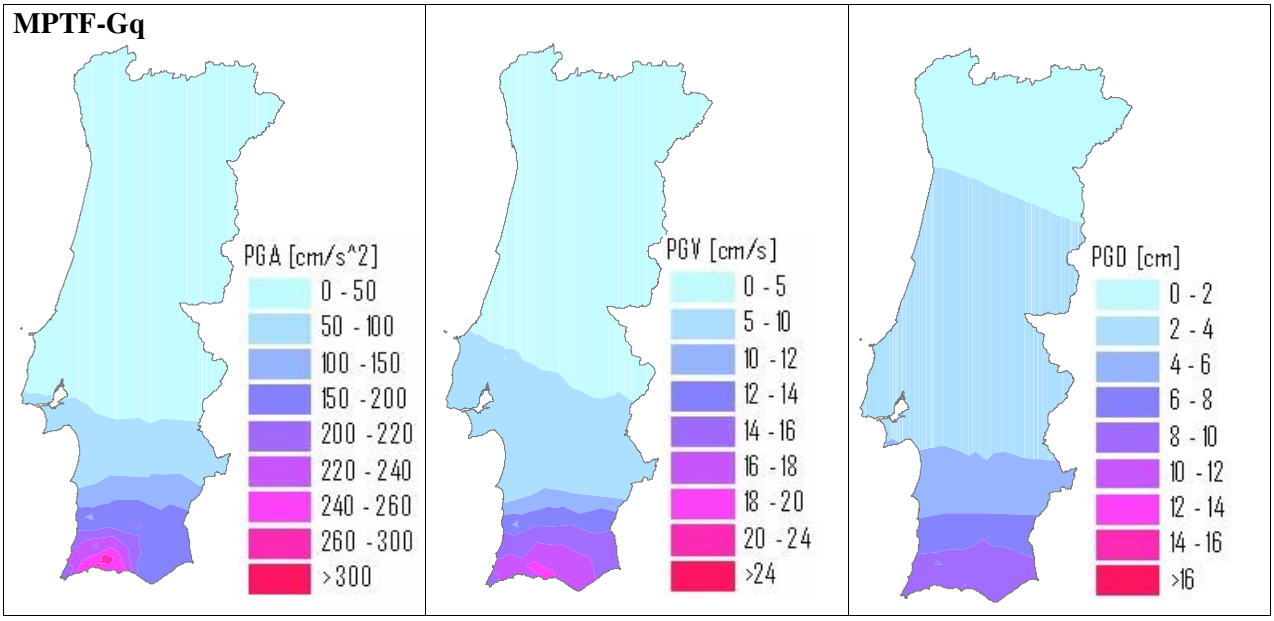

Figure 7. Peak ground acceleration, peak ground velocity and peak ground displacement at the bedrock level, for the MPTF-Gq fault source geometry

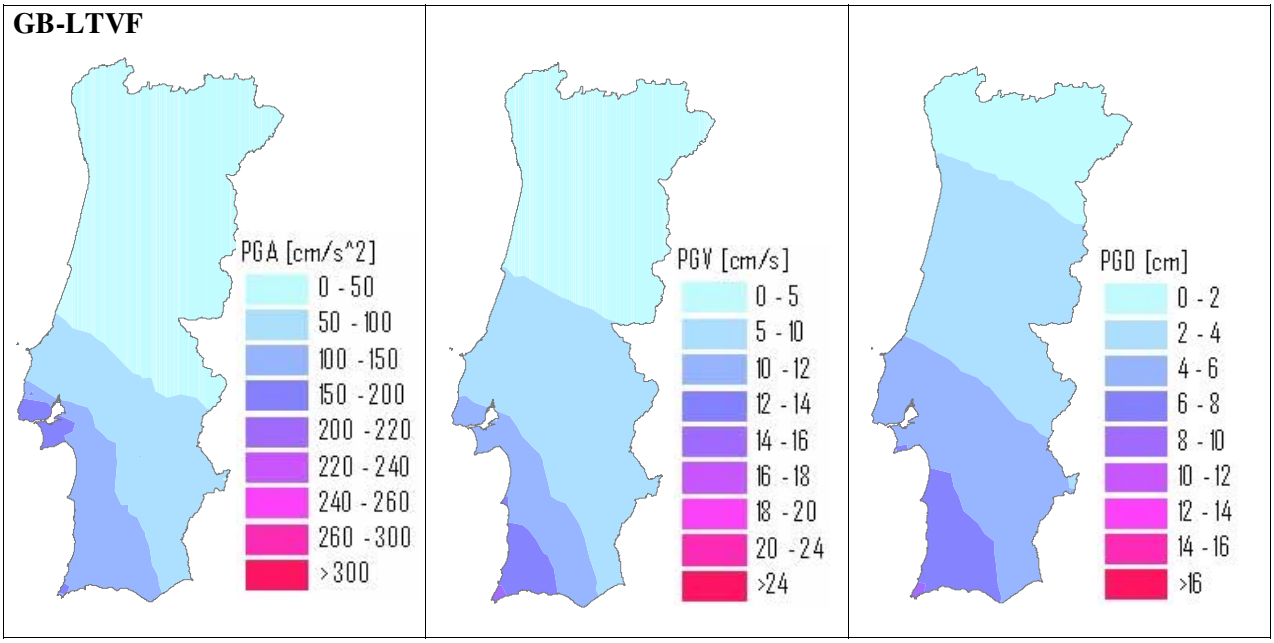

Figure 8. Peak ground acceleration, peak ground velocity and peak ground displacement at the bedrock level, for the GB-LVT fault source geometry.

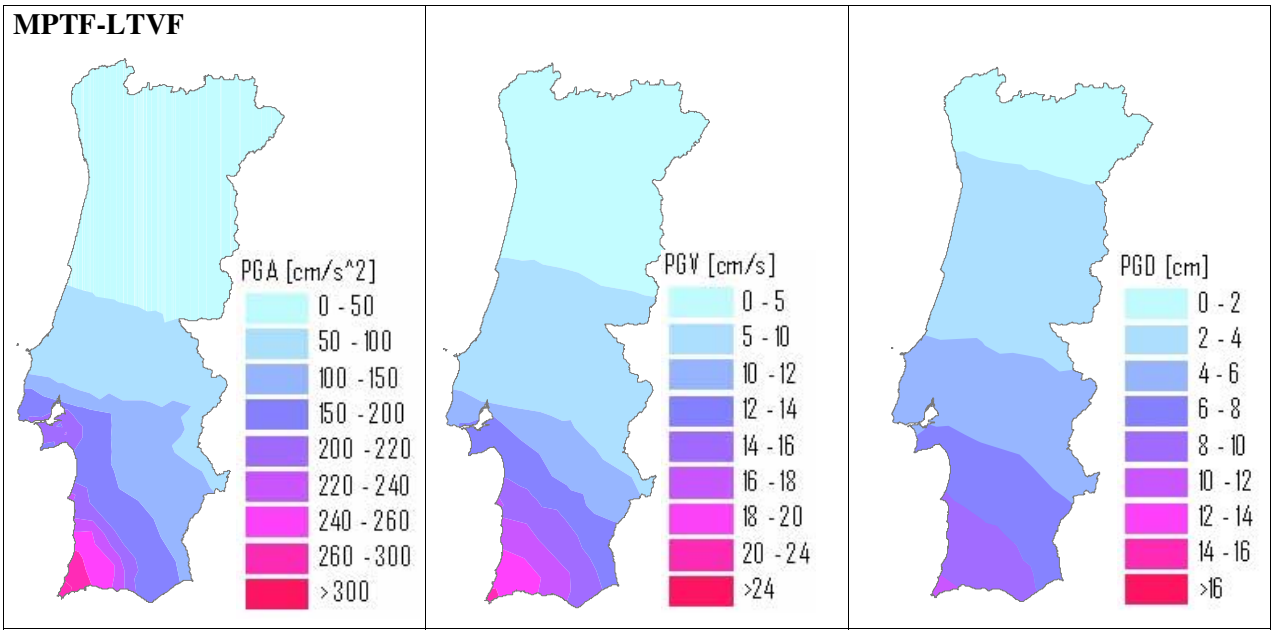

Figure 9. Peak ground acceleration, peak ground velocity and peak ground displacement at the bedrock level, for the MPTF-LTVF fault source geometry.

Analyzing these input motion maps we conclude that both the system Marques Pombal Thrust Fault and Pereira de Sousa fault (MPTF – PS) and the multiple rupture offshore and at LVTF (specially the MPTF-LVTF geometry) are the best candidates to the source of the 1755 Lisbon earthquake as they reproduce quite well the pattern of intensities at a national level. The MPTF as a single source can not reproduce intensities along Portuguese coast, because of its reduce dimensions, and the composite source of MPTF and Guadalquivir Bank (MPTF-Gq model) in spite of producing a quite good fit of the isoseismal distribution at the south of Portugal, do not produce such a good fit along the coast, indicating that should be a northward prolongation of the MPTF, as proposed by Terrinha [23] or Vilanova [25].

To emphasize the grade of interrelation between some seismic parameters obtained for each fault geometry and intensities of the earthquake, the rank correlation coefficient of Spearman is calculated. The Spearman rank correlation coefficient between two variables X and Y, is given by the relation [Siegel [27], Elenas [28]]:

$$\rho_S = 1 - \frac{6\sum_{i=1}^{N} D^2}{N\left(N^2 - 1\right)} \tag{11}$$

where D denotes the difference between the ranks of corresponding values of Xi and Yi and N is the number of pairs of values (X,Y) in the data.

Table 4 presents the correlation coefficients between peak ground acceleration (PGAb), peak ground velocity (PGVb) and peak ground displacement (PGDb) for bedrock, spectral pseudo-acceleration (SA) for 1Hz and spectrum intensity of Housner (SI) and intensities of the earthquake. As pointed out by Elenas [28] it is supposed that a correlation coefficient up to 0.5 means low correlation, a coefficient in the range [0.5-0.8] means medium correlation, while a coefficient greater than 0.8 means strong correlation.

Table 4. Correlation coefficients of Pearson between peak ground acceleration (PGAb), peak ground velocity (PGVb) and peak ground displacement (PGDb) for bedrock, spectral pseudo-acceleration (SA) for 1Hz and spectrum intensity of Housner (SI) and intensities of the earthquake.

	MPTF	**MPTF-PS**	**MPTF-Gq**	**GB-LVT**	**MPTF-LVT**
PGAb	0.829	0.838	0.822	0.845	0.830
PGVb	0.822	0.841	0.824	0.844	0.822
PGDb	0.818	0.846	0.825	0.842	0.816
SA	0.831	0.836	0.827	0.850	0.831
SI	0.821	0.838	0.826	0.845	0.821

In our opinion, results should be analyzed with relatively distance due to the fact that there are a great number of councils with the same intensity allowing a great dispersion in the correlation. On the other hand, all models, because of attenuation law, can reproduce higher intensities at the South and lower intensities at the North of Portugal, which will turn out in a good correlation with real intensities. Nevertheless, stronger correlations are obtained for the MPTF-PS and GB-LVT geometry models.

CONCLUSION

Current methods of predicting ground motions for future earthquakes in Portugal should be based on an assumed seismological model of source and propagation processes. Complementary work should include the use of strong motion records when available and of physical models of propagation with all lateral heterogeneities existing in the passage of the oceanic to the continental crust.

Small to moderate magnitude events should be recorded at sites where strong motions of the target events are going to be simulated. For this purpose, high-resolution accelerographs must be deployed at selected sites of Portugal.

Limits of the seismological models and results are naturally given by the used parameters, namely the stress drop and kappa parameters. Factors that affect strong ground motions, as surface topography or Q gradients along the propagation path, are not including in the model. However, the aim of our study was to prove the ability of the source models for estimating the intensities felt at the time of the earthquake, and not to provide definitive ground motion values.

Regarding the proposed geometries for the source of the 1755 Lisbon earthquake, the system Marques Pombal Thrust Fault and Pereira de Sousa (MPTF-PS model) or the suggestion of a rupture at the Lower Tagus Fault induced by stress changes seem good candidates to the source of the 1755 Lisbon earthquake as they reproduce quite well the pattern of isosseismal.

Empirically spectral accelerations may take values of about 0.03g in Lisbon (Ambraseys [29]; Boomer [30]). Such small PGA values hardly can justify macro seismic intensities observed. The 0.25 – 0.3g now estimated (plus 20% accounting for soil effects) is a more reliable value showing that the seismological model allowed a more realistic simulation of the large magnitude historical earthquake and that is an efficient method that can accommodate the necessity of earthquake ground motion perditions for engineering applications in Portugal.

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