

A Finite – Fault Modeling of the 1755 Lisbon Earthquake Sources

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ABSTRACT

This work uses a non-stationary stochastic seismological model, based on random vibration theory, for calculating response spectra and synthesizing strong ground motion acceleration records for Portugal Mainland. The validation of the method and comparison with strong ground motion records for Portugal are entirely carried out in terms of 5% damped pseudo absolute response spectra for acceleration. The calibrated model is used to simulate ground motion acceleration for the 1755 Lisbon earthquake. Five potential source rupture models that have been recently proposed by several authors for the 1755 Lisbon earthquake are tested: two analytical models based on hydrodynamic studies; two models based on seismic surveys and one from a recent suggestion based on induced stress changes.

For all models, peak ground acceleration maps are compared with iso-intensities map of the earthquake in order to test the ability of the source models for estimating the intensities of the earthquake. The peak ground motion is calculated for different unknown parameters like the rupture velocity, the slip distribution and the nucleation point. The fault parameters like dimension, dip and strike are the ones proposed by the authors of the different analysed source models.

INTRODUCTION

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. However, differences in the regional geology can lead 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.

The strong ground motion prediction based on finite-fault simulation requires the identification of the fault (strike, dip, length and width), source kinematics parameters (stress drop, velocity of rupture), regional crustal properties (geometrical spreading, anelastic structure, amplification and attenuation upper crust parameters, etc) and the determination of amplification effects due to the local site geology.

The model parameters calibration has been done with a dataset that includes horizontal components of ground acceleration records (hard sites) obtained by the Portuguese digital accelerometer network. Validation and comparison are entirely in terms of 5% damped pseudo absolute response spectra for acceleration.

The demonstrated agreement between model and data for low to moderate events in Portugal provides strong grounds for accepting the stochastic-process model predictions for this type of events and to use it as the basis for characterization of stronger earthquakes considering a finite fault rupture modeled as a sum of a number of point sources distributed spatially and temporally.

Being so, the calibrated model is used to simulate ground motion acceleration for the 1755 Lisbon earthquake, considering different source models proposed in literature. For

each possible source a suite of models was performed varying the rupture velocity, the nucleations points and slip distribution, kinematic parameters that are unknown for the 1755 earthquake. The soil effect was taken into account considering a nonlinear behaviour of the stratified geotechnical sites conditions. The simulated intensity is compared with the observed intensity values.

NUMERICAL APPROACH

The non-stationary stochastic finite fault simulation method [Carvalho et al., 2004] differs from the classic FINSIM developed by Beresnev and Atkinson [1998] as it obtains the ground motion parameters from the Fourier amplitude spectrum using random vibration theory and extreme values statistics instead of generating synthetic accelerograms. The method starts estimating the acceleration Fourier amplitude spectrum, which is a result of contributions from earthquake source, path and site and is defined by

$$A(\omega, R) = \omega^2 \cdot C \cdot S(\omega) \cdot G(R) \cdot An(\omega, R) \cdot P(\omega) \cdot F_Z(\omega) \cdot F_r(\omega)$$

where C is a scaling factor, $S(\omega)$ is the displacement source spectrum, $G(R)$ is the geometric attenuation factor, $An(\omega, R)$ is the anelastic path attenuation factor, $P(\omega)$ accounts for the upper crust attenuation, $F_Z(\omega)$ is an amplification function and $F_r(\omega)$ is a regional correction function. The functional form of all these factors and the respective physical meaning can be found elsewhere [eg. Boore, 2003; Carvalho et al., 2004, Ferrer& Sanchez-Carratalá, 2004].

Taking into account the Fourier amplitude spectrum, $A(\omega, R)$, and a given source duration, T_s , it is possible to derive the one-sided power spectral density function (PSDF) of acceleration by means of:

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

The PSDF of the response of the oscillator with a circular frequency ω_n and a damping ratio ζ assuming a stationary process, is calculated as:

$$S_x(\omega, \omega_n, \zeta) = Sa(\omega) |H_x(\omega, \omega_n, \zeta)|^2$$

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.

Any stationary response moments of order k is defined as

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

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

$$\lambda_k(t, \omega, \omega_n, \zeta) = \theta^2(t, \omega_n, \zeta) \cdot \lambda_k(\omega, \omega_n, \zeta)$$

in which the response modulating function, θ , is obviously dependent of frequency and damping of the one degree of freedom system and can be found in Carvalho *et al.* [2005].

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, λ_k^T , can be estimated as the sum of all subfault response moments, meaning that:

$$\lambda_k^T(t, \omega, \omega_n, \zeta) = \sum_{j=1}^N \theta_j^2(t, \omega_n, \zeta) \cdot \lambda_{k_j}(\omega, \omega_n, \zeta)$$

Considering the extreme values statistics and taking T as the duration of the earthquake, the non-stationary response spectrum of the displacement that synthesizes the integration of all the delayed ruptures over the fault is [Vanmarcke, 1976]

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

where

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

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

being δ the bandwidth parameter defined as

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

Comparison of response spectra obtained with the non-stationary stochastic finite fault simulation method and with FINSIM classic can be seen in an accompanying paper (Zonno *et al.*, 2005).

Once the non-stationary response spectra has been achieved, an 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 (LNECLoss – Sousa *et al.*, 2004) that was developed at LNEC.

MODEL CALIBRATION

The dataset used includes horizontal components of ground acceleration records obtained by the portuguese digital accelerographic network, on hard sites. The regional distribution of the earthquakes epicenters is illustrated in Figure 1 and parameters of these earthquakes are given in Table 1. Some of the events were recorded in more than one station. The distribution of accelerograms with earthquakes magnitudes and distances is shown in Figure 2.

As in other countries, M_w is not routinely determined for Iberia events, and instead, the size of an earthquake is characterized in terms of multi-mode guided surface-wave magnitude, M_{LG} or surface-wave magnitude, M_S . For the determination of seismic moment, we used a relationship for the conversion of M_S to $\log(M_0)$ provided by Ambraseys & Free [1997] which is suitable for the European area and explicitly takes into consideration focal depth.

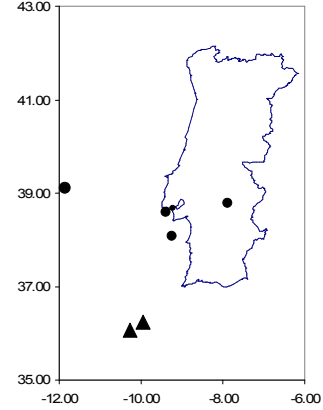


Fig. 1. Epicentral distribution of the earthquakes records. The size of circles is proportional to the value of magnitude. Circles: Intraplate earthquakes Triangles: Interplate earthquakes.

TABLE 1. List of earthquakes recorded by digital network of Lisbon. Last column specifies the class: intra-plate and inter-plate earthquakes.

Event	Date	Mw	Lat.	Long.	Class
1	31-07-1998	4.4	-7.88	38.79	Intra
2	20-09-1999	4.7	-9.39	38.59	Intra
3	16-10-2000	4.1	-9.23	38.68	Intra
4	28-03-2002	4.5	-9.25	38.08	Intra
5	24-07-2002	4.8	-11.86	39.11	Intra
6	29-07-2003	5.3	-10.26	36.07	Inter
7	13-12-2004	5.3	-9.96	36.25	Inter

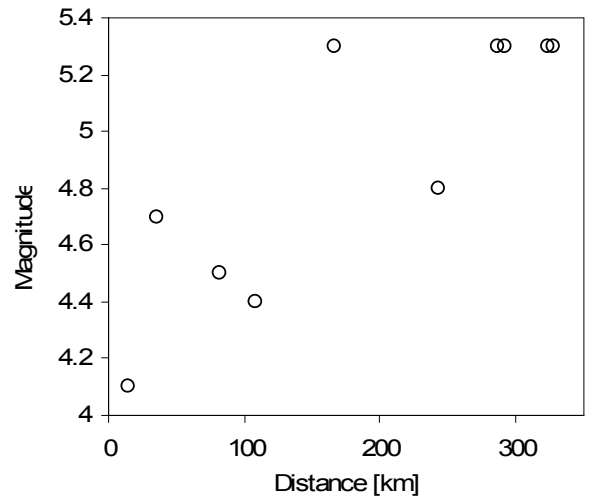


Fig. 2. Distribution of ground motion data for rock sites by magnitude and distance.

Simulation parameters were inferred by comparison of synthetic and observed response acceleration spectra (5% dumping). Results of model parameters are represented in table 2 and figure 3 shows some examples of response spectra comparison between synthetic and observed data.

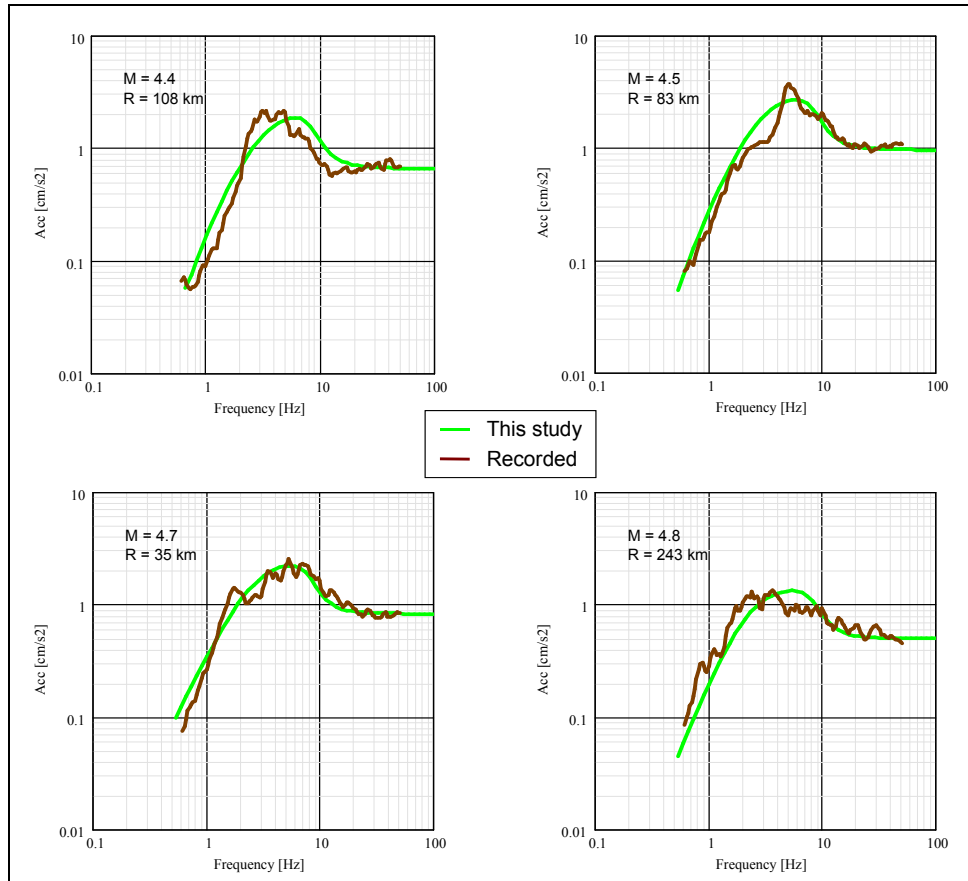


Figure 3 Example of response spectra comparison between synthetic and observed data.

TABLE 2. Finite Fault Model Parameters for offshore -inland sources

Parameters	Intraplate	Interplate
Crustal thickness, D	25km	
Quality factor, $Q(f)$	$239 \cdot f^{-1.06}$ (*)	
Geometric attenuation	$1/R$ ($R \leq 1.5D$ km) $1/R^0$ ($1.5D$ km < $R \leq 2.5D$ km) $1/R^{0.5}$ ($R > 2.5D$ km)	
Distance-dependent duration	$0.02 R$ ($R > 300$ km) 0 ($R < 300$ km)	
f_{max}	10Hz	7Hz
kappa, k	0.0s	0.052s
Shear-wave velocity, β	3.5 km/s	
Crustal density, ρ	2.8 g/cm ³	
Stress drop, $\Delta\sigma$	120bar	50bar
Amplification function $F_z(\omega)$	1	$F_z(\omega) = \frac{2}{1 + \left(\frac{\omega_i}{\omega}\right)^2}$ $\omega > \omega_i$ $\omega_i = 0.35$
Regional correction $F_r(\omega)$	$F_r(\omega) = \frac{\alpha}{\sqrt{1 + \left(\frac{\omega}{\omega_r}\right)^2}}$ $\alpha = 1.15, \omega_r = 0.35$	1

(*) Vales et al. [1998]

1755 LISBON EARTHQUAKE

Source models

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 $M_w = 8.5 - 8.9$ by several authors [e.g. Abe, 1979; Moreira, 1984]. The exact location remains controversial, even though the earthquake epicentre is known to have been offshore.

The several isoseismal maps published (eg. Figure 4) led to the conclusion that the source location of this event was in the vicinity of Gorringe Bank (GB, Figure 5) [Martinez Solares, 1979; Levret, 1991]. This location was further supported by the occurrence of a tsunamigenic earthquake on 1969.02.28.

Baptista *et al.* [1998] 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.

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 2001] was the characterization of the active tectonic structure located offshore Cape St. Vicente named as Marques Pombal thrust fault (MPTF, Figure 5) which, accordingly to the authors, could be the generator of the 1755 Lisbon earthquake, near the epicentre location $37^\circ N$ $10^\circ W$ obtained by Rodriguez [1940] (red circle, Figure 5).

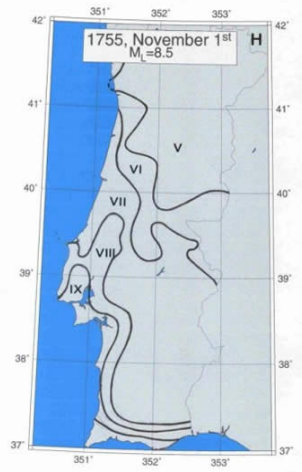


Figure 4. Isoseismal of the 1755 earthquake from Moreira [1984].



Fig. 5. Structural features. GB-Gorringe Bank (Thrust fault); MPTF-Marques Pombal Thrust Fault; Gq –Guadalquivir Bank; PS – Pereira de Sousa Fault; LTVF – Lower Tagus Valley Fault. Red circle show epicentral locations proposed by different authors and used in this study, for the Lisbon 1755 earthquake: coordinates 37°N-10°W, proposed firstly by Rodriguez [1940].

Terrinha *et al.* [2003] 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 5) located along the Portuguese margin, to the north of MPTF, could constitute the northward prolongation of the MPTF. This localization is compatible with Baptista *et al* [1998] numerical modeling.

Baptista *et al.* [2003], 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 5), which, accordingly to authors, will act as a possible southeastward extension of the rupture area related to the 1755 event.

Vilanova *et al* [2003] propose that, although the main shock was offshore, the resulting static stress changes induced the rupture of the Lower Tagus Valley (LTVF, Figure 5), near Lisbon. They favor this model, rather than 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.

For the offshore model, Vilanova *et al.* [2003] chose Gorringe Bank between all the epicentral locations proposed by different authors to test the hypothesis of earthquake triggering under the least favorable conditions (the most distant from the LTV Fault).

Modeling geometry

Using the stochastic finite fault method explained above, we have tested four different fault source geometries for the source of the 1755 earthquake proposed by the different authors.

For all geometries, fault segments were divided into smaller subfaults, 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 moment do not change.

Figure 6 presents the fault source geometries and the different nucleation points considered. The geometry named MPTF considers the proposal of Zitellini *et al.* [2001], the geometry MPTF-PS considers the proposal of Terrinha *et al.* [2003] and the model MPTF-Gq considers the new study of Baptista *et al.* [2003]. The last model, considers besides the main shock in MPTF, a second earthquake in Lower Tagus Valley Fault (LTVF) as proposed by Vilanova *et al.* [2003].

Gorringe Bank as an offshore source is not considered in this study as Baptista *et al.* [1998] already showed that Gorringe Bank is a very unlikely location for the 1755 event because it leads to wrong travel times of tsunami.

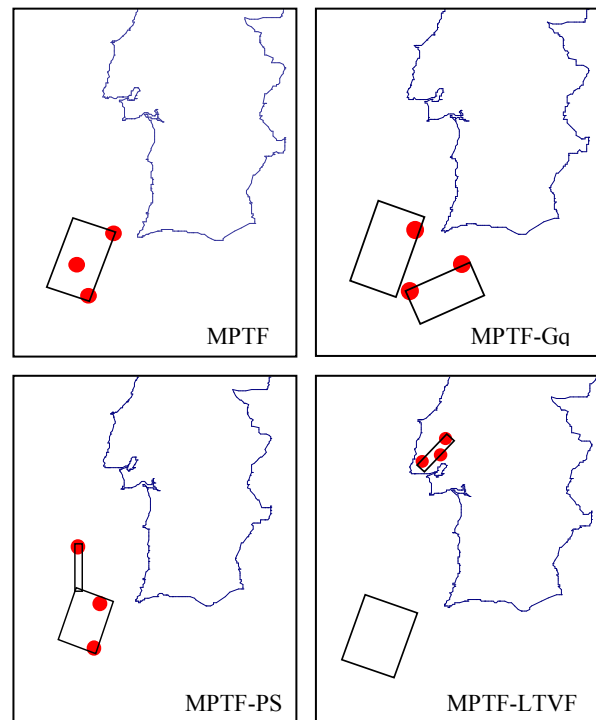


Fig 6. Surface projection of fault source geometries considered in this study, based on source models proposed by different authors (see text). Red circles are the different nucleation points considered. The nucleation points at Marques Pombal fault in MPTF-LTVF model are the ones represented in MPTF model.

Results and discussion

For each fault geometry seismic action was computed at the bedrock level. Results for random slip distribution, for the

MPTF, MPTF-Gq and MPTF-PS for each nucleation point, are shown in figures 7 to 9.

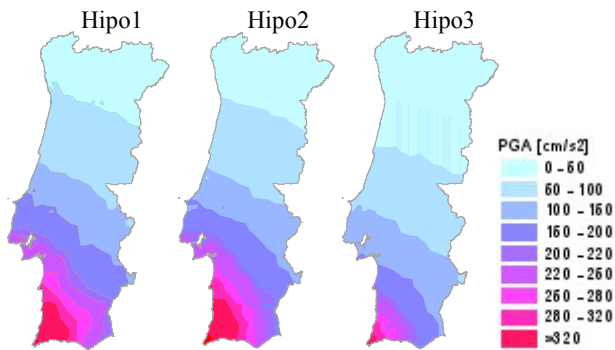


Fig. 7. Peak ground acceleration at bedrock level, for the MPTF fault source geometry. Hipo 1, 2 and 3 are nucleation points from south to north, respectively, in figure 6.

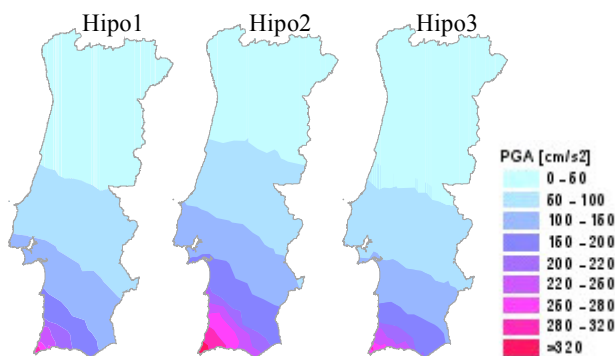


Fig. 8. Peak ground acceleration at bedrock level, for the MPTF-Gq fault source geometry. Hipo 1, 2 and 3 are nucleation points from south to north, respectively, in figure 6.

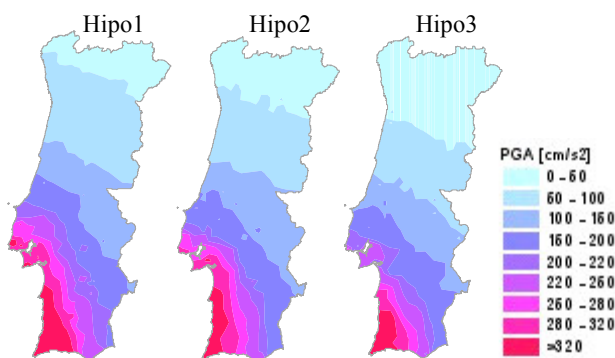


Fig. 9. Peak ground acceleration at bedrock level, for the MPTF-PS fault source geometry. Hipo 1, 2 and 3 are nucleation points from south to north, respectively, in figure 6.

The MPTF as a single source can not reproduce intensities along Portuguese coast, showing a radial and circular pattern. A downward propagation (Hipo3) shows too low values in Lisbon, that can not justify the intensities that occurred and an upward propagation (Hipo1) gives too high values in south (some cities have PGA values at bedrock of more than 600 cm/s^2) and interior of Portugal.

The composite source of MPTF and Guadalquivir Bank (MPTF-Gq model) in spite of producing a good fit of the isoseismal distribution at the south of Portugal, do not produce a good fit along the coast, showing too low PGA values, indicating that should be a northward prolongation of the MPTF, as proposed by Terrinha *et al.* [2003] or Vilanova *et al.* [2003].

Concerning the MPTF-PS model, the directivity effect is very clear. An upward propagation (Hipo1) gives too high values at LTV when compared to south of Portugal but an downward propagation (Hipo3) with the initiation of rupture near Lisbon (about 120 km) results in a good agreement with what is expected to have occurred. It is visible an effect around LTV that will be even more clear when accounting for the soil effect. Figure 10 presents the time duration for Portugal considering Hipo3 as the nucleation point, and the synthetic time histories for Lisbon and Lagos (black point SW of Portugal) considering MPTF-PS model, and nucleation points Hipo1 and Hipo3.

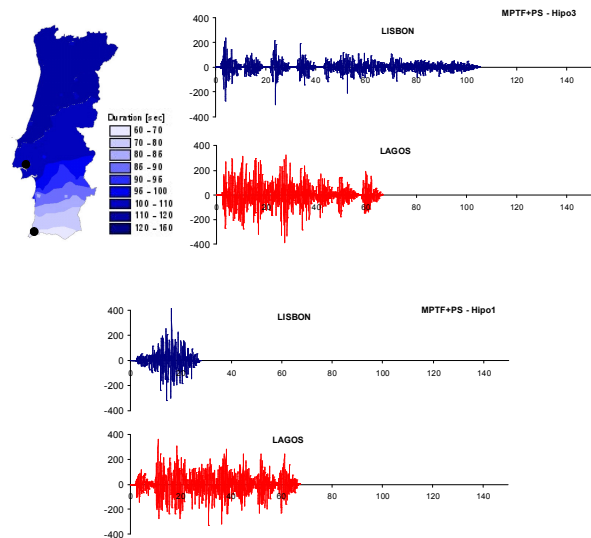


Fig 10: Map: Time duration for Portugal mainland, considering MPTF-PS model and nucleation point Hipo3. Time history (PGA, cm/s^2) considering the same model. Up: nucleation point Hipo3; Down: nucleation point Hipo1.

Figure 11 presents results for the MPTF-LTVF model, for the three nucleation points considered in figure 6, considering a M6.8 inland and the hipo3 for the nucleation point in MPTF, the one we consider gives reasonable results for south of Portugal..

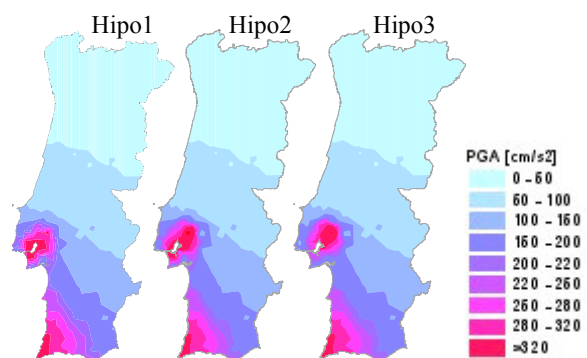


Fig. 11. Peak ground acceleration at bedrock level, for the MPTF-LTVF source geometry. Hipo 1, 2 and 3 are nucleation points from south to north, respectively, in figure 6.

It seems this model fits well the pattern pattern of intensities. However, a M6.8 seems a too high magnitude for the inland earthquake. Figure 12 presents the synthetic time histories for Lisbon considering MPTF-LTVF model, and the three nucleation points.

As proposed by Vilanova (personal communication) we considered a 3 minutes gap between the offshore earthquake and the local rupture.

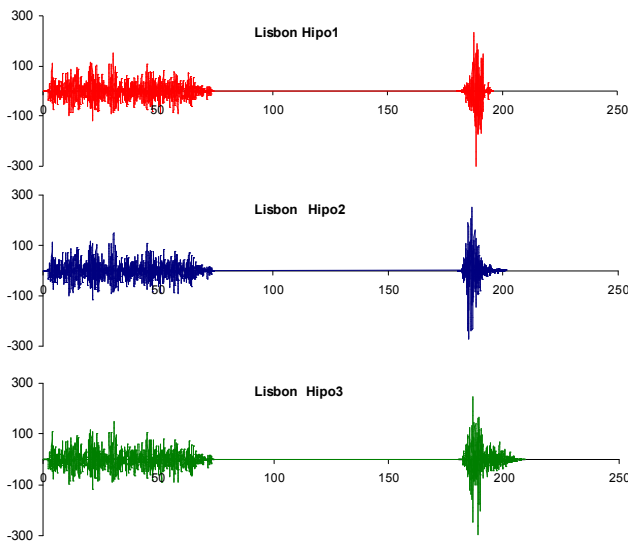


Figure 12. Time history (PGA, cm/s^2) for Lisbon, considering the model MPTF-LTVF, with the nucleation point Hipo3 in MPTF, and for the three nucleation points shown in figure 6.

CONCLUSIONS

A non – stationary stochastic method was applied to test four different models that have been taken as possible for the source of the 1755 earthquake.

Carvalho *et al.* [2004] had performed a similar study, using the same methodology and the same source models proposed by several authors. In that study only a bilateral propagation was performed, with one nucleation point, and no attempt was done to study the effect of directivity, using different nucleation points. In addition, results were presented with modeling parameters not calibrated for Portugal mainland, but instead, using data from East North America, whose response spectra have often been considered to be representative of intraplate conditions around the world.

Analyzing the most complete study performed here and its results we conclude that both the system MPTF – PS, considering a downward propagation and a nucleation point 120 km away from Lisbon, and the multiple rupture offshore at LTVF (the MPTF-LTVF geometry) are the best candidates to the source of the 1755 Lisbon earthquake as they can satisfactory reproduce the pattern of intensities at a national level.

Other considerations, namely the possibility of each source to produce a tsunami, the time arrivals of tsunami, the geological evidences, the consequent damage and so on, are left to others.

Current methods of predicting ground motions for future earthquakes in Portugal will/should be based on an assumed seismological model of source and propagation processes.

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REFERENCES

Abe K. [1979] "Size of great earthquakes of 1837 – 1974 inferred from tsunami data." *J. Geophys. Res.*, 84:1561-1568.
 Ambraseys, N. N.; Free, M. W. [1997] "Surface-wave magnitude calibration for European region earthquakes". *Journal of Earthquake Engineering*, V. 1, N. 1, 1-22.

Baptista M. A., Miranda P. A., Miranda J. M., Mendes Victor L. A. [1998] "Constraints on the source of the 1755 Lisbon Tsunami inferred from numerical modelling of historical data on the source of the 1755 Lisbon Tsunami." *J. Geodynamics*; 25(2): 159-174.
 Baptista, M.A., Miranda, J.M., Chierici, F., Zitellini, N. [2003] "New study of the 1755 earthquake source based on multi-channel seismic survey data and tsunami modeling," *Natural Hazards and Earth System Sciences*, 3, pp. 333-340.
 Beresnev, I.A.; Atkinson, G.M. [1998] "FINSIM - a FORTRAN program for simulating stochastic acceleration time histories from finite fault," *Seism. Res. Lett.*, 69, pp. 27-52.
 Boore, D.M. [2003] "Simulation of ground motion using the stochastic method," *Pure Appl. Geophys.* 160, pp. 635-676.
 Carvalho, A.; Campos Costa, A.; Sousa Oliveira, C. [2004] "A stochastic finite-fault modeling for the 1755 Lisbon earthquake," 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 2194
 Carvalho, A.; Campos Costa, A.; Sousa Oliveira, C. [2005] "Non – stationary stochastic modeling for portugal mainland. Estimates of the spectral parameters from weak to moderate earthquakes ($m < 5.5$)," (to be submitted)
 Ferrer, I.; Sánchez-Carratalá, R. [2004] "Application of non-stationary seismological models to the determination of stochastic response spectra", 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004 Paper No. 2280
 Levret A. [1991] "The effects of the November 1, 1755 Lisbon earthquake in Morocco." *Tectonophysics*; 193: 83-94.
 Martinez Solares J. M., Arroyo L., Mezcuca J. [1979] "Isosseismal map of the 1755 Lisbon earthquake obtained from spanish data." *Tectonophysics*, 56(3): 301-313.
 Moreira V. [1984] "Sismicidade histórica de Portugal continental" *Sup. Revista Instituto Nacional de Meteorologia e Geofísica, Lisboa* (in portuguese)
 Rodriguez, G. [1940] "Catálogo sísmico da zona compreendida entre los meridianos 5E e 20W de Greenwich y los paralelos 25N y 45N." Tomo I. *Inst. Geog. Nac., Madrid*.
 Sousa, M.L., Campos Costa A., Carvalho, A., Coelho, E. [2004] "An automatic seismic scenario loss methodology integrated on a geographic information system," 13th World Conference on Earthquake Engineering Vancouver, B.C., Canada August 1-6, 2004, No. 2526
 Terrinha P., Pinheiro L. M., Henriet J. P., Matias L., Ivanov M. K., Monteiro J. H., Akhmetzhanov A., Volkonskaya A., Cunha T., Shaskin P., Rovere, M. [2003] "Tsunamigenic – seismogenic structure, neotectonics, sedimentary process and slope instability on the southwest Portuguese margin." *Marine Geology*; 195: 55-73.
 Vales, D.; Fitas, A.; Oliveira, C. S.; Senos, L.; Ramalheite, D.; Carrilho, F. [1998] "Atenuação inelástica para o norte e centro de Portugal". *APMG* (abstract, in portuguese).
 Vanmarcke E. H. [1976] "Structural response to earthquakes", *Seismic Risk and Engineering Decisions*, 1976; C.Lomnitz and E. Rosenblueth, Reditors, Elsevier.
 Vilanova, S., Catarina, F., Nunes, Fonseca, J.F.B.D. [2003] "Lisbon 1755: A Case of Triggered Onshore Rupture?," *Bull. Seismol. Soc. Am*, Vol. 93, No. 5, pp. 2056-2068.
 Zitellini, N., Mendes, L. A., Cordoba, D., Danobetia, J., Nicolich, R., Pellis, G., Ribeiro, A., Sartori, R., Torelli, L., Bartolome, R., Bortoluzzi, G., Calafato, A., Carrilho, F., Casoni, L., Chierici, F., Corela, C., Corregiari, A., Della-Vedova, B., Garcia, E., Jornet, P., Landuzzi, M., Ligi, M., Magagnoli, A., Marozzi, G., Matias, L., Penitenti, D., Rodriguez, R., Rovere, M., Terrinha, P., Vigliotti, L., Zahinos-Ruiz, A. [2001] "Source of 1755 Lisbon earthquake, tsunami investigated," *EOS* 82, No. 26, pp. 285–291.
 Zonno, G.; Carvalho, A.; Franceschina, G.; Akinci, A.; Campos Costa, A.; Coelho, E.; Cultrera, G.; Pacor, F.; Pessina, V.; Cocco, M. [2005] "Simulating earthquake scenarios using finite-fault model for the Metropolitan Area of Lisbon (MAL)", this volume.