Simulating Earthquake Scenarios Using Finite-fault Model for The Metropolitan Area of Lisbon (MAL)

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ABSTRACT

In the framework of the ongoing European project "*LESSLOSS – Risk Mitigation for Earthquakes and Landslides*", finite-fault seismological models are proposed to compute the earthquake scenarios for three urban areas – Istanbul (Turkey), Lisbon (Portugal) and Thessaloniki (Greece). For each case study, ground motion scenarios are developed for the most probable two events with different return periods, locations and magnitudes derived from historical and geological data. In this study, we simulate the accelerometric time series and response spectra for high frequency ground motion in the city of Lisbon and surrounding counties (Metropolitan Area of Lisbon), using two possible earthquake models: the inland source area of Lower Tagus Valley, **M** 5.7 (4.7) and a hypothesis of the offshore source area of the 1755 Lisbon, **M** 7.6. The stochastic and a new hybrid stochastic-deterministic approach, DSM are used in order to evaluate the ground shaking and to characterize its spatial variability. Results are presented in terms of Response Acceleration Spectra (PSA), Peak Ground Acceleration (PGA) and Peak Ground Velocity (PGV) respect to rock site. Then the site effects are evaluated by means of an equivalent stochastic non-linear one-dimensional ground response analysis of stratified soil profile units properly designed. A sensitive study is performed using different input parameters and different approaches in order to give the basic information to evaluate the range of uncertainty in seismic scenarios.

INTRODUCTION

The project "LESSLOSS – Risk Mitigation for Earthquakes and Landslides" is an European integrated project developed within the framework of the Sixth Programme for Research, Technological Development and Demonstration of the European Commission. The subproject 10, SP10, examines earthquake disaster scenario predictions and loss modeling for the three cities: Istanbul, Lisbon and Thessaloniki (Figure 1). In this paper only the case study of Lisbon will be presented.

The overall aim of SP10 is to create a tool, based on state-of-the art modeling software, to provide strong quantified statements about the benefits and costs of a range of possible mitigation actions, to support decision-making by city and regional authorities for seismic risk mitigation strategies.
For each case study, ground motion scenarios are developed for the most probable two events with different return periods, locations and magnitudes derived from historical and geological data. The strong ground motion prediction requires the identification of the position, geometry and rupture mechanism of active faults, the knowledge of local elastic and anelastic structure of the crust and the determination of amplification effects due to the local site geology.
Moreover even in case of an 'a priori' fixed fault source parameter model, the comparison of synthetic seismograms computed with different procedures requires a careful check of the numerical description of the source and propagation models. The problem of the computation of site transfer functions to be used to evaluate ground motion at surface is also a topic investigated in the project. Some activities are devoted to issues mostly related to site characterization and site response assessments through a comparison of different methods selected for three countries.

The seismic risk of Lisbon derives partly from large offshore events, such as that which caused the catastrophic 1755 disaster, and was damaging over a very wide area; and partly from local events situated in or near the Metropolitan Area of Lisbon (MAL), such as the 1909 Benavente earthquake, which was locally destructive.
We simulate the accelerometric time series and response spectra for high frequency ground motion in the city of Lisbon and surrounding counties, using the stochastic and a new hybrid stochastic-deterministic approach.
The site effects are evaluated by means of an equivalent stochastic non-linear on-dimensional ground response analysis of stratified soil profile using the LNECloss system. The system, given a seismic scenario (magnitude and location) and the option of seismological model, computes the Power Spectral Density Function (PSDF) of the strong ground motions at bedrock and surface level of any site at a given epicentral distance using the Bedrock Seismic Input and Local Soil Effect software modules.
A sensitive study is performed varying the rupture velocity, the propagation direction depending on nucleation points and using different approaches in order to give the basic information to evaluate the range of uncertainty in seismic scenarios.
The evaluation of the worst hazard scenario depending on level of shaking is done selecting the more conservative parameters at each parish in terms of Response Acceleration Spectra (PSA) and Peak Ground Acceleration (PGA) respect to rock site and to surface. Then, the worst risk scenarios, out the scope of this paper, considering casualties and level of damage of buildings will be performed with the application of the loss model to the Metropolitan Area of Lisbon, using the LNECloss system [Sousa et al., 2004].

NUMERICAL APPROACHES

Some numerical methods have been adopted for the prediction of strong ground motion due to extended faults: a hybrid stochastic-deterministic approach [DSM-Deterministic-Stochastic Method; Pacor et al., 2005] was used for all three investigated urban areas, while a non-stationary stochastic finite fault simulation method [FINSIM-LNEC; Carvalho et al., 2004] was applied in the case of Lisbon, for offshore events.

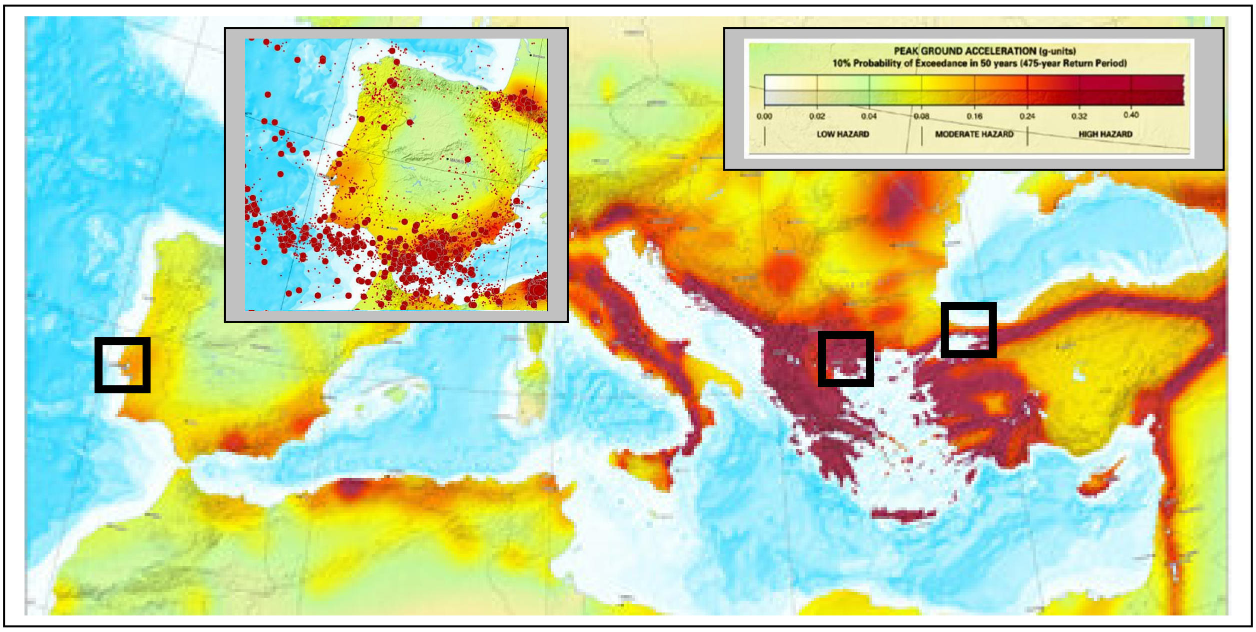


Fig. 1. The three investigated urban areas (black boxes) are drawn: Lisbon (Portugal), Thessaloniki (Greece) and Istanbul (Turkey). Underlying the Seismic Hazard Map of the European-Mediterranean region, in terms of peak ground acceleration at a 10% probability of exceedance in 50 years for stiff soil condition [from Jiménez et al., 2003]. A spot (top left) is showing the instrumental seismicity (1980–2004) border the Portugal (range **M** 4.0-6.0).

Furthermore, in the case study of MAL, the classic computer program FINSIM [Beresnev and Atkinson, 1997, 1998] has been used for a comparison of the other methods DSM and FINSIM-LNEC. The DSM approach is based on a modification of the stochastic approach of Boore [2003] (Point-Source-Stochastic-Method – PSSM) using synthetic ground motion envelopes with a simplified isochron formulation. In extremely schematic form, the synthesis of any time series is a four-step procedure:

1. An acceleration envelope radiated from an extended fault is computed by solving a simplified formulation of the representation theorem through the isochron formulation (Bernard and Madariaga, 1984; Spudich and Frazer, 1984) for a defined kinematic rupture process; the Green functions are computed as asymptotic solution of the elastodynamic equation (ray theory) in a flat-layered velocity model;
2. A time series of Gaussian white noise is windowed with the deterministic envelope, which is smoothed and normalized so that the integral of the squared envelope is unity;
3. The windowed-noise time series is transformed into the frequency domain and multiplied with a point-source-like amplitude spectrum. The parameters of reference spectrum (i.e., corner frequency, distance from the fault, and radiation pattern) are evaluated through the kinematic model to capture the finite-fault effects;
4. Transformation back to the time domain.

The DSM method has been applied to simulate strong ground motions close to the seismic source for a reference earthquake, the September 26, 1997, Umbria-Marche mainshock and for its sequence of aftershocks [Bindi et al., 2004]. The main conclusion of the above analysis is that the simulated ground motion at bedrock sites shows a good fit with the real one, modeling the directivity effect too. The directivity effects are extremely important to explain the variability of ground motion time histories at near source distances, i.e. within distances smaller than 2-3 time the fault length. The DSM method is capable of capturing the complexity of near-source ground motion, even when input data regarding earthquake source, propagation medium, and site characteristics are of a very schematic nature.

The other method, the classic computer program FINSIM [Beresnev and Atkinson, 1998a], is based on stochastic finite-fault modeling technique which combines the stochastic ground-motion modeling technique with the kinematic model of rupture propagation [Beresnev and Atkinson, 1997, 1998b]. FINSIM is a well known program and has been worldwide used to simulate ground motion both from earthquake of moderate [Berardi et al. 2000; Castro et al 2001; Roumelioti et al., 2004] and high magnitude [Atkinson and Beresnev, 2002; Roumelioti and Beresnev, 2003; Ruiz-Cruz and Castro, 2004].

The third method FINSIM-LNEC that is implemented in the LNECloss system is based on “non-stationary stochastic finite fault simulation method” [Carvalho et al., 2004]. This program differs from the classic FINSIM [Beresnev and Atkinson, 1998a] 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.

In extremely schematic form, the synthesis of the evaluation of the PSDF - Power Spectral Density Function computed by FINSIM-LNEC is given in the following step procedure:

1. Estimate of the Fourier amplitude spectrum;
2. Estimate of total duration of ground motion (source duration and path dependent duration);
3. Estimate of non-stationary response spectra;
4. Iterative estimate of equivalent stationary PSDF using the classical theory of stationary random process.

The applied techniques allow the computation of synthetic time series and response spectra for direct S-wave field at bedrock sites and are suitable to generate shaking scenarios near an extended fault whereby the direct S wave-field is generally dominant in amplitude with respect to the reflected and superficial phases. The earthquake scenarios have been computed for bedrock sites. Generally, to include the local site effects, the computed seismic bedrock scenarios have been adopted as input motion for a 1D analysis at representative sites with a detailed soil categorization and were then corrected introducing site transfer functions derived from experimental data and from numerical modeling [i.e. Jiménez et al., 2000; Wills et al., 2000]. In the case of Lisbon, instead, the characterization of local soil effects is taken into account, computing the Power Spectra Density Function (PSDF) directly at the surface level considering also the non-linear behavior of stratified geotechnical soil profile.

THE CASE OF METROPOLITAN AREA OF LISBON

In the European project LESSLOSS have been selected three case study cities in regions of moderate to high seismic hazard and where strong ground motions data are scarce or not available: Istanbul, Lisbon and Thessaloniki (Figure 1). The Metropolitan Area of Lisbon (MAL), which is under study in this paper, has been historically stricken by scarce, though intense, earthquakes, such as the offshore 1755 Lisbon earthquake, the offshore Gorringe Bank earthquake (1969) and earthquakes (1531, 1909) caused by the rupture of local intra-plate faults [Oliveira, 1986; Oliveira and Sousa, 1991]. The simulation of Earthquake scenarios using finite fault-model is needed to estimate more realistic level of hazard. The procedure to derive a dominating scenario event at a site from a Probabilistic Seismic Hazard Analysis (PSHA) involves the evaluation of hazard de-aggregation. This type of analysis has already been extensively discussed and applied specifically in Portugal, namely Lisbon Metropolitan region [Campos Costa et al., 2002], Azores islands [Carvalho et al., 2001] and to a broader geographic region comprising Portugal mainland [Montilla et al., 2002, Sousa, 2005]. LNEC [Campos Costa et al., 2002; 2005] performed the de-aggregation process evaluating hazard marginal distributions in terms of latitude and longitude and of expected M value. This procedure permits, as pointed out by Bazurro and Cornel [1999], a direct display on a map of location of sources dominating the hazard allowing, along with the knowledge of the most likely magnitude, a better establishment of the specific earthquake that presents the greatest hazard to the site. In this way, inter-plate and intra-plate seismic scenarios can be independently assessed.
In practice, to evaluate seismic hazard scenarios the following procedure was implemented [Campos Costa et al.,2005]:

i. Perform a Probabilistic Seismic Hazard Analysis (PSHA) for a site (parishes of MAL) and generate a hazard curve - a mixed model was used considering gross source zones to compute *b* values of Gutenberg Richter law, maximum magnitudes and annual rates geographically uniform bins to obtain spatially seismic rates;
ii. Determine the contribution factor of each geographic bin (x,y) for that particular site and intensity level (return period);
iii. Identify the geographic bin (x,y) with the modal value of the contribution;
iv. Define the hazard consistent magnitude for that particular geographic bin.

On the basis of some de-aggregation of probabilistic hazard there are mainly two seismic sources that could be critical for MAL and that are representative respectively of short and long return periods: (a) the inland source area of Lower Tagus Valley (near Lisbon area) and (b) the likely offshore source area of the 1755 Lisbon earthquake.

TABLE 1. The values of magnitude represented are the highest expected magnitudes assessed for each location from a previous de-aggregation analysis of Campos Costa et al. [2005].

10 years			**475 years**			**1000 years**		
Lat.	Long.	Mag.	Lat.	Long.	Mag.	Lat.	Long.	Mag.
-9.5	38.9	4.3	10.75	36.0	8.1	-10.8	36.0	8.2
-9.1	**38. 8**	**4.6**	-9.8	36.6	7.8	-9.8	36.6	8.1
-9.1	39.1	4.3	**-9.6**	**36.9**	**7.6**	**-9.6**	**36.9**	**7.9**
-8. 8	38.9	5.0	**-9.1**	**38.8**	**5.7**	-9.1	38.8	5.9
			-9.1	39.1	5.6	-9.1	39.1	5.7
			-9.0	39.3	5.4	-9.0	39.3	5.7
			-8.8	38.9	6.3	-8.8	38.9	6.4

To simulate strong ground motions for MAL we have selected, on the basis of return period (Table 1), three seismic scenarios: the first two are located respectively offshore (epicenter 9.6W 36.9N; magnitude Mw = 7.6) and inland (9.1W 38.8N, magnitude Mw = 5.7), both with 500 years return period. The latter is located inland (9.1W 38.8N, magnitude Mw = 4.7) and it is representative of a return period of 50 years.

On 1 November 1755 the city of Lisbon was struck by an earthquake which magnitude was evaluated as close to 8.7 [Richter, 1958; Johnston, 1996].

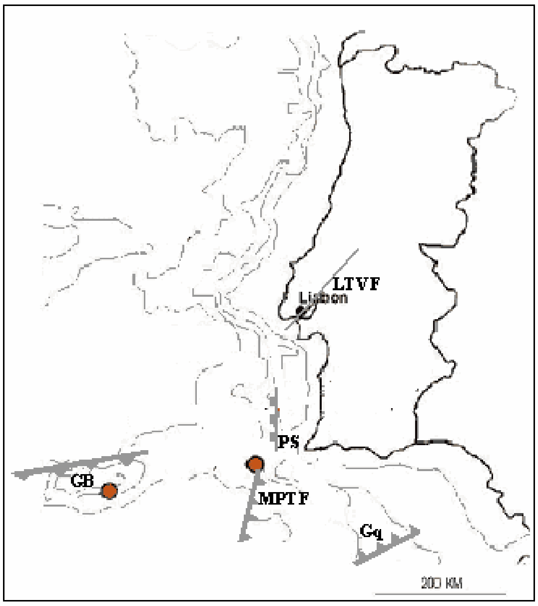


Fig. 2. Structural features: GB-Gorringe Bank Thrust fault geometry; MPTF- Marques Pombal Thrust Fault; Gq –Guadalquivir Bank; PS – Pereira de Sousa Fault; LTVF – Lower Tagus Valley Fault. Red circles show epicentral locations proposed by different authors for the Lisbon 1755 earthquake [from Carvalho et al., 2004].

This earthquake, known as the 1755 Lisbon earthquake, generated the largest known tsunami in SW Europe but the exact location remains controversial [Vilanova et al., 2003; Carvalho et al., 2004]. The offshore seismic scenario event (epicenter 9.6W 36.9N; magnitude Mw = 7.6) is located in a possible source area of the 1755 Lisbon earthquake and, in this study, we use for it the characterization of the active tectonic structure located offshore Cape St. Vicente named Marques Pombal Thrust Fault (MPTF) as a single source candidate [Zitellini et al., 1999, 2001]. The values of dip and strike of MPTF were taken from Baptista et al, [2003]. The red circle, near MPTF (Figure 2) shows the epicentre location 10W 37N obtained by Rodriguez [1940] that is very close to the selected offshore scenario (9.6W 36.9N).
The inland seismic scenarios (9.1W 38.8N, magnitude Mw = 5.7 and Mw = 4.7) are located in the Lower Tagus Valley (LTV) near to Vila Franca Fault [Vilanova and Fonseca, 2004; Cabral et al., 2004] very close to the most densely populated and heavily industrialized area of Lisbon.

FINITE-FAULT MODEL PARAMETERS

For the earthquake scenarios, selection of the possible earthquake source locations, its geometrical, kinematical structure and parameters and the starting point of fault rupture are very important issues. Therefore, the finite-fault simulations require specification of the fault-plane geometry (length and the width, etc.), source (stress drop) and the crustal properties of the region (geometrical spreading coefficient, quality factor, etc.) and the site-specific soil response information.

In this paper, we perform a bedrock ground motion simulation of acceleration and velocity for three scenarios based on the mentioned possible sources. Scenario I: the offshore MPTF fault, with length (along the strike) of 110 km and width (down-dip) of 24 km corresponding to an event of **M** 7.6; scenario II: the inland LTVF, with length of 8.4 km and width of 6.0

corresponding to **M** 5.7 and scenario III: the inland LVTF with length of 2.2 km (width of 2.8 km) which corresponds to **M** 4.7. The fault dimensions as a function of moment magnitude are calculated using the empirical relations of Wells and Coppersmith [1994]. The fault geometry and the source mechanisms are given in Table 2.

TABLE 2. Geometry and dimension of seismic sources

Sources	**(1) Offshore**	**(2) Inland**	**(3) Inland**
Return period	500 year	500 year	50 year
Magnitude Mw	7.6	5.7	4.7
L(km)*W(km)	110 x 24	8.4 x 6.0	2.2 x 2.8
Center of fault	36.90N; 9.90W	38.82N; 9.05W	38.82N; 9.05W
Origin of fault	36.46N; 9.92W	38.82N; 9.05W	38.82N; 9.05W
Strike (degree)	20	220	220
Dip (degree)	24	55	55
Depth of fault	4.5 km	0.5 km	2.0 km

The model parameters calibration have been done with a dataset that includes horizontal components of ground acceleration records (hard sites) obtain by the national digital accelerometer network of Lisbon (Table 3).

TABLE 3. List of earthquakes recorded by digital network of Lisbon. Last column specifics 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

In figure 3 is shown the *K* estimations from the slope of the high frequency acceleration spectrum

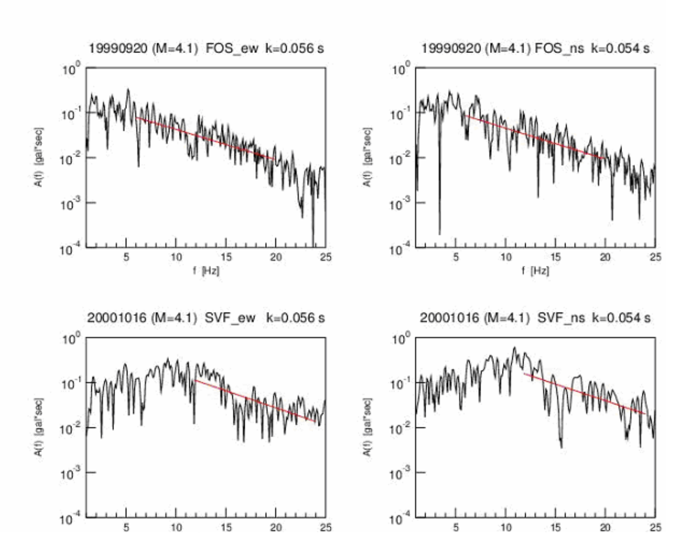


Fig. 3. K estimations from the slope of the high frequency acceleration spectrum. WE and NS amplitude Fourier spectra of the direct S wave pulse are shown in the left and right panels respectively. Top and bottom panels refer to events 2 and 3 of Table 2. respectively

The other parameters, including crustal properties and sources calibration parameters to complete the finite fault simulation were obtained after calibration from digital data and are given in Table 4. [Carvalho et al., 2004].

To perform a comparison of methods and a sensitivity analysis, 5 points have been selected corresponding to 5 test parishes (Figure 4): North (S021, Alcoentre), South (S268, Sesimbra (Santiago)), East (S250, Santo Isidro de Pegões), West (S137, Colares) and in the Middle (S174, Alverca do Ribatejo).

TABLE 4. Finite Fault Model Parameters for offshore -inland sources

Parameters/Sources	MPTF	LTVF
Q(f) = Qo f*η	Qo = 239 η =1.06	
Geometric spreading	1/R (R ≤ 37.5 km) 1/37,5 - 37.5 km < R ≤ 125 km 1/137.5* sqrt(125/R) if R>125	
Distance-dependent duration (sec)	1/fo for R < 300 km; (1/fo + 0.05R) for R> 300 km	
Stress drop	50 bars	120 bars
Parameter *sfact*	1.0	1.0
Sub-fault along strike and dip: (+) FINSIM; (*) DSM	(+) 20 x 5	(+) 10 x 10 (*) 20 x 10
Crustal amplification		1
Bedrock parameter K	0.0	0.055
Shear wave velocity,	3.5 km/sec	
Rupture velocity	2.5 km/sec	
Crustal density	2.8 gr/cm^3	
Slip distribution model	Given	homogeneous
Number of trials		30

The extension of the MAL region is about 100 km x 80 km. The LTVF fault is located in the middle of the area, so that each parish is no more than about 50 km far from the fault. Figure 4 shows the surface projection of the faults used for the shaking scenario simulation

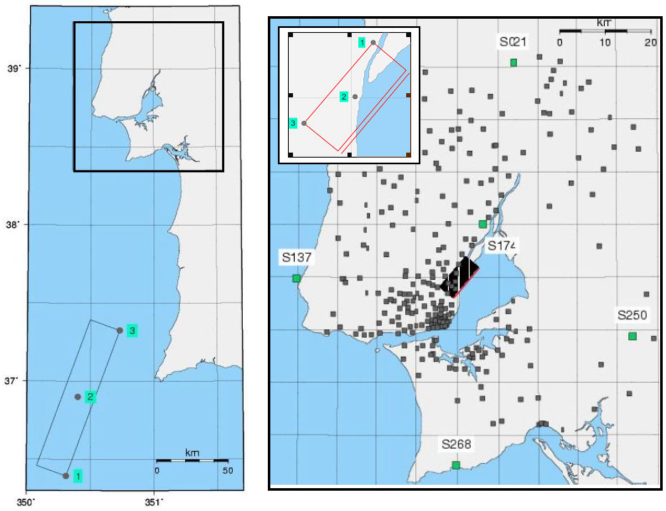


Fig. 4. Left: geometry of offshore MPTF **M** 7.6 respect to the MAL (black box). Right: the 276 parishes (black dots) and the 5 test parish points S021, S268, S250, S137 and S174. A spot of the assumed LTVF **M** 5.7 is shown on the left top. Numbers in each fault are the different nucleation points assumed.

The variability in the prediction of strong motion parameters was introduced selecting different rupture propagations and slip distributions. The nucleation points were located in the half deepest part of the fault (Figure 4). The simulation results were grouped according to the position of the nucleation points in three areas of the fault and with three rupture propagation.

The different simulations were classified using a code IJK as follows: slip distribution (I: 0=homogeneous; 1=given); velocity of rupture (J: 1=2,5 km/s.; 2=2.7 km/s and 3=2.9 km/s) and position of nucleation point (K: 1=Unilateral NE/SW; 2=Bilateral and 3=Unilateral SW/NE).

In case of LTVF **M** 5.7 we use a homogeneous slip distribution while for the MPTF **M** 7.6 the simulations are computed for three different slip models assuming that the slip has a Gaussian distribution, located on the different nucleation points: n.1, n.2 and n.3 (Figure 5).

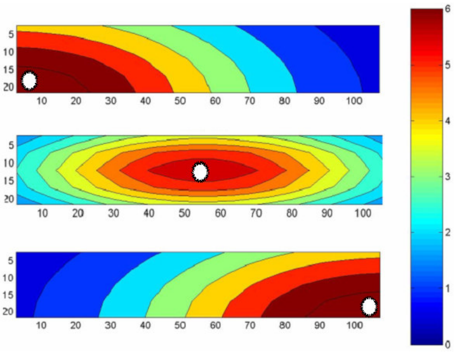


Fig. 5 MPTF fault: three different slip distribution model that are related (from the top) to the case of nucleation points n1, n2 and n.3. The total amount of slip is the same but with Gaussian distribution centered on the different nucleation points.

RESULTS OF SENSITIVITY ANALYSIS

*The case of inland source LTVF **M** 5.7*

In the following we present a comparison of the response spectra obtained at 5 test points using FINSIM-LNEC, FINSIM and the DSM methods. Figure 6 shows the response spectra (5 % damping) obtained from bilateral rupture using the DSM, FINSIM-LNEC and FINSIM techniques with a rupture velocity of 2.8 km/sec (0.8 x Vs) for the inland source LTVF **M** 5.7.

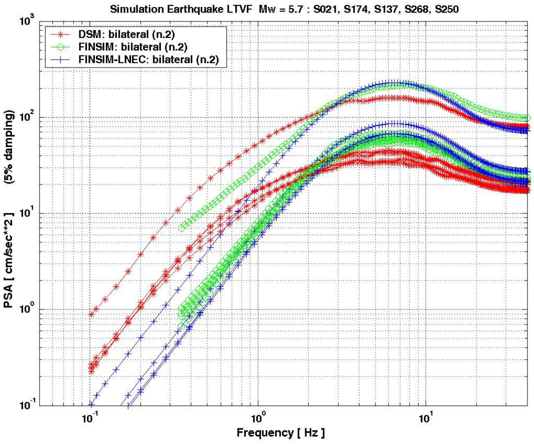


Fig. 6. Comparison of response spectra PSA (5 % damping) obtained with bilateral rupture (code 022) by DSM, FINSIM-LNEC and FINSIM with a rupture velocity of 2.8 km/sec.

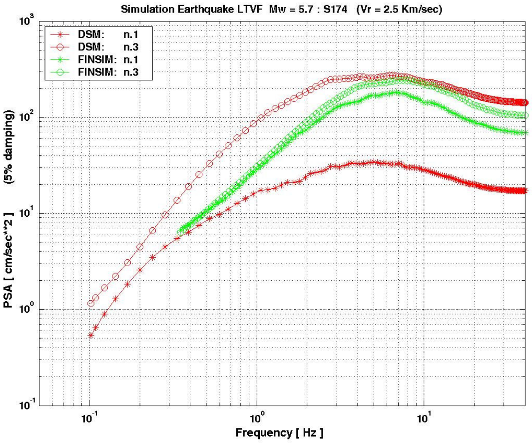


Fig. 7. Sensitivity of response spectra of seismic source LTVF **M** 5.7 to alternative parameters: rupture velocity of 2.5 km/sec and nucleation points (n.1 = code 011 and n.3 = code 013). The DSM and FINSIM simulated spectra are computed to the test point S174 located in the middle of MAL and resulting to be the closest point to the fault (about 10 km).

The PSA computed with the three codes (Figure 6) are similar for frequencies higher than 2 Hz at all five selected sites. Since the test point S174 is the closest point to the fault, it gives a higher peak ground motion (PGA around 0.2 g). Figure 7 remarks the efficacy of DSM method to model the directivity effects. In fact at site S174, the PSA values obtained with code 011 (backward directivity) are much lower (about factor 2) than the ones computed with the code 013 (forward directivity). There is also a little effect of directivity on the results of the classic FINSIM (Figure 7, green curves) but only at higher frequency.

Figure 8 shows the PSA response spectra computed by DSM at the 5 test points. An increase of directivity effects can be observed at all sites according to their position respect to the nucleation point.

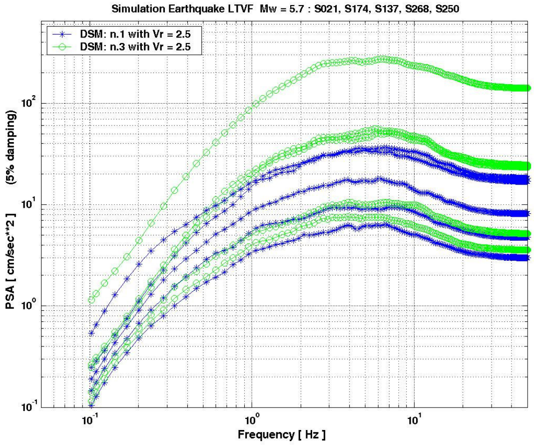


Fig. 8. Sensitivity of PSA response spectra (LTVF **M** 5.7) to alternative parameters: rupture velocity of 2.5 km/sec and nucleation points: n.1 (code 011) and n.3 (code 013).

We also simulated the spectra for the five selected parishes using DSM method for different rupture velocity of 2.5 and 2.9 km/sec, in order to see the sensitivity of ground motions to the rupture velocity. An increase of directivity effects can be observed at all sites for increasing values of the rupture velocity. However, due to the high value of the high frequency decay parameter k used for the simulations, the effect of the rupture velocity is small (Figure 9).

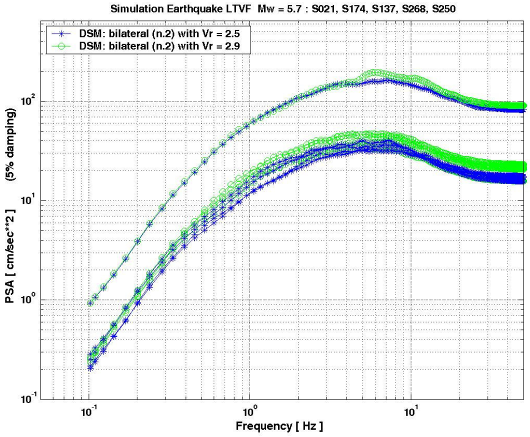
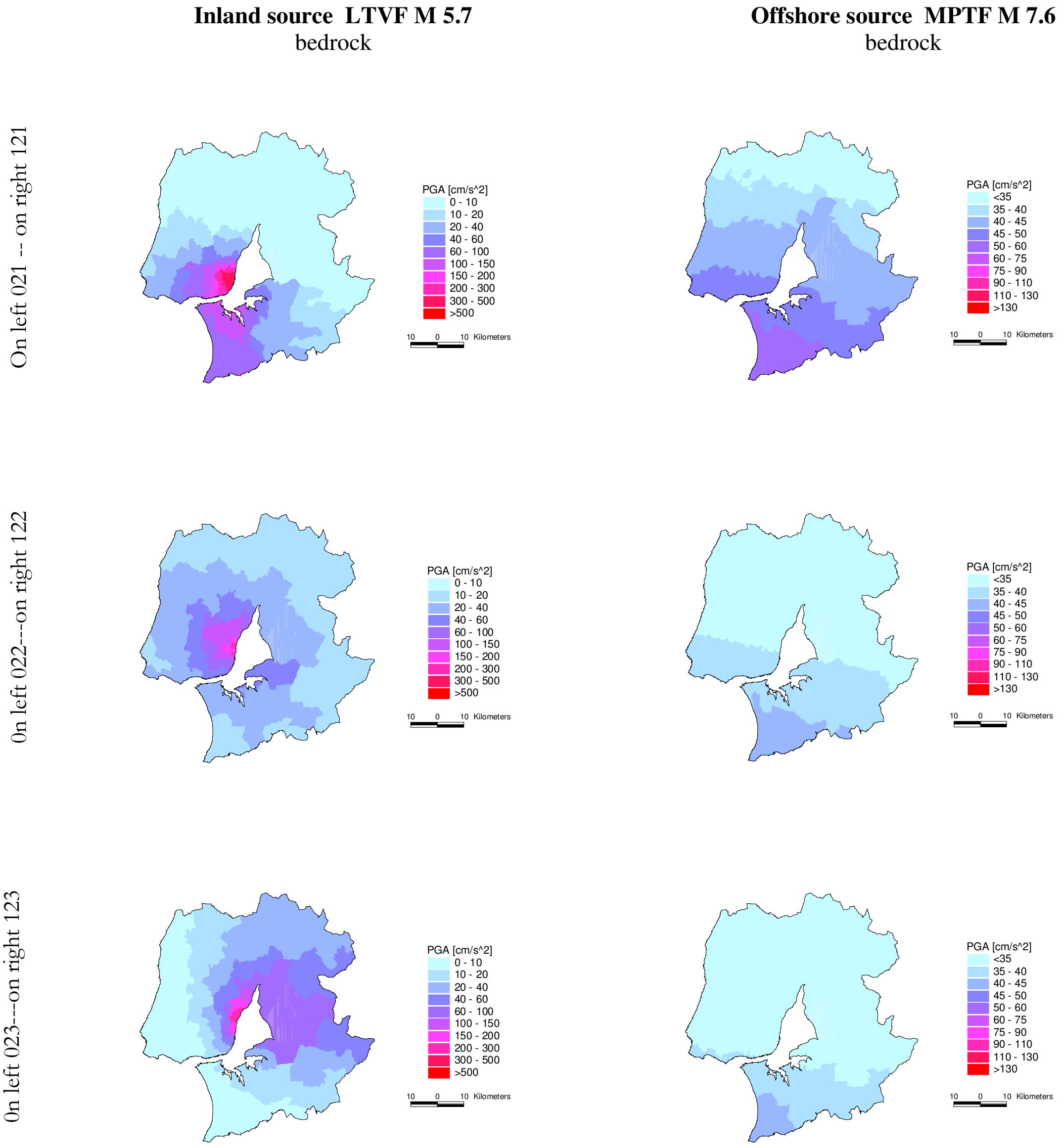


Fig. 9. Sensitivity of PSA response spectra (LTVF **M** 5.7) to alternative parameters: rupture velocity of 2.5 km/sec and nucleation points: n.1 (code 011) and n.3 (code 013).

We have also observed the sensitivity of the ground motion to the position of the nucleation point along the fault segment. The PSA values estimated using DSM seems more sensitive to the rupture directivity than FINSIM. Therefore we decide to use DSM method, which is more accurate in the description of the spatial variability, in order to simulate the inland source of Lower Tagus Valley Faults



Inland source LTVF M 5.7
bedrock

Offshore source MPTF M 7.6
bedrock

On left 021 -- on right 121

On left 022---on right 122

On left 023---on right 123

Fig. 10. Left: the MAL's PGA maps obtained with DSM method applied to the inland source LTVF **M** 5.7. Right: the MAL's PGA maps obtained with FINSIM-LNEC method applied to the offshore source MPTF **M** 7.6. All the maps are relative to alternative nucleation points: n.1, n.2 and n.3 with rupture velocity of 2.5 km/sec.

Since the DSM simulations, in case of large seismic sources (with M>7.0), need for specific calibration, the offshore scenario were, instead, modeled with FINSIM-LNEC.

*The case of offshore source MPTF **M** 7.6*
In this case, we perform a bedrock ground motion simulation of acceleration and velocity for offshore scenario (Table 2). A comparison has been done with the classic FINSIM using the same parameters. Although the trend of the curves is the same some differences of FINSIM-LNEC in respect to the classic FNSIM are observed: a) the response spectra are more smoothed; b) the response spectra obtained have lower values for frequency less than 1 Hz (this fact is due to the non-stationary component); c) the behavior of the curves on the 5 test point shows more scatter, that means the method is more sensitive to different nucleation points.

EVALUATION OF SEISMIC SCENARIOS

Bedrock sites scenarios. The results have been provided in terms of time series, PSA and maps of different shaking parameters as PGA, PGV (PGD) for each scenario.

In respect to the seismic scenarios performed for the inland source LTVF we have computed the seismic ground motion at the bedrock using the DSM method. For each of 276 parishes of MAL response spectra (30 trials) have been produced, together with average time durations. The LNECloss system transforms them into Power Spectrum Density Function (PSDF) at the bedrock.

In respect to the seismic scenarios performed for the offshore source MPTF we have computed directly the PSDF at the bedrock using the FINSIM-LNEC method implemented in the LNECloss system.

The peak ground acceleration PGA obtained with DSM method applied to the inland source LTVF **M** 5.7 are shown on the left of Figure 10. The directivity effects coming from different rupture propagation on the fault are well marked: directivity effects are shown in the case 023 and 021 (bottom and top figures, respectively, on the left of Figure 10).

The PGA values obtained with FINSIM-LNEC method applied to the offshore source MPTF **M** 7.6 are illustrated on the right of Figure 10.

Surface sites scenarios. The above numerical approaches evaluate time series, response spectra or PSDF (Power Spectral Density Function) of the strong ground motion at bedrock level, but site amplification effects has to be considered for refined ground shaking scenarios.

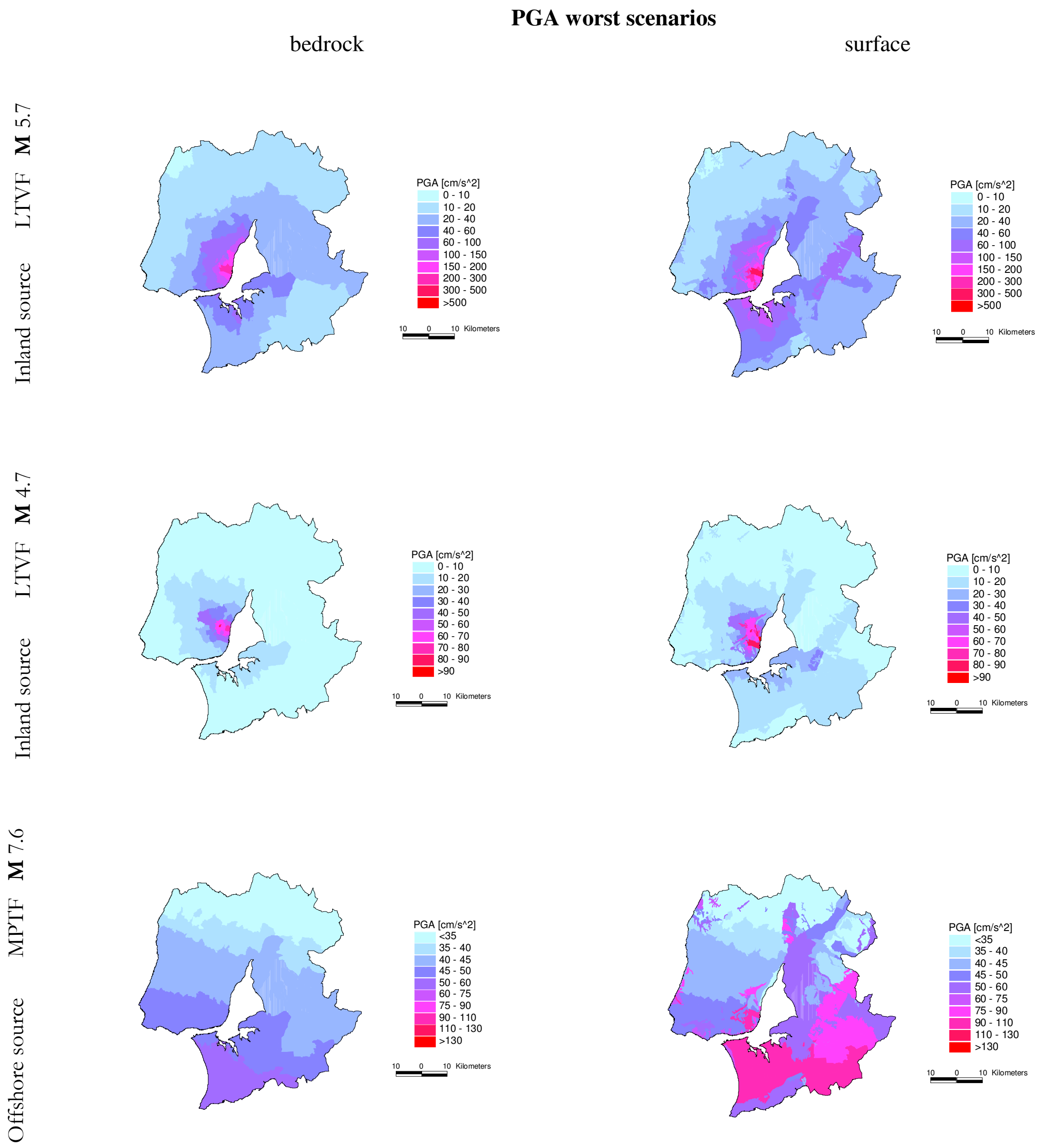


Fig. 11. Left: the worst scenarios at the bedrock. Right the worst scenarios at the surface level obtained with the LNECloss system.

A data base is available, containing information on stratified soil profile units for the region under analysis: in the framework of the project conducted by the national civil protection authority [SNPC, 2003], it was carried out a geological - geotechnical survey that allowed the characterization of stratified soil profile units for MAL. The computer algorithms developed and implemented inside LNECloss system introduce some major improvements to take into account site effects due to soil dynamic amplification in rather efficient way [Serra and Caldeira, 1998].

Figure 11 presents the worst shaking scenario, in terms of PGA, for the considered sources. The worst scenario is defined considering, in each parish, the maximum value of shaking parameters of all scenarios (9 in the case of inland **M** 5.7 and offshore **M** 7.6, and 3 in case of inland **M** 4.7). In each parish, the worst response spectra is obtained selecting, for each frequency, the maximum spectral ordinate among the values generated by the hypothesized scenarios at bedrock.

To estimate the worst scenario of ground shaking on the surface, the same methodology was applied.

CONCLUSIONS

In the framework of the LessLoss project we have estimated ground motion scenarios in the frequency band of engineering interest (0.5-20 Hz) for the Metropolitan Area of Lisbon.

The shaking scenarios are computed in terms of Response Acceleration Spectra (PSA), time series, peak ground acceleration (PGA) and peak ground velocity (PGV) at bedrock and surface level.

Two numerical methods have been adopted for the prediction of strong ground motion due to extended faults: a hybrid stochastic-deterministic approach (DSM-Deterministic-Stochastic Method; Pacor et al., 2005) and a non-stationary stochastic finite fault simulation method (FINSIM-LNEC; Carvalho et al., 2004). To include the local site effects the LNECloss system have been used that takes into account them computing the surface Power Spectra Density Function.

The obtained PGA values for some parish, very close to the LTVF **M** 5.7, reach the value of 0.7 g while for the LTVF **M** 4.7 and MPTF **M** 7.6 scenarios very small values of peak ground acceleration are estimated.

The worst shaking scenarios for the Metropolitan Area of Lisbon have been delineated both at the bedrock and surface level considering the computation at level of parishes.

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