Paper No **1700**

# SIMULATING EARTHQUAKE SCENARIOS IN THE EUROPEAN PROJECT LESSLOSS: THE CASE OF 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**" two sub-projects are devoted to earthquake disaster scenario predictions and loss modeling for urban areas and infrastructures.

This poster is dealing with the sub-project 10, **SP10**, Task Programme "Scenario earthquake definitions for three cities". 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 poster only the case study of Lisbon will be presented.

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 non-stationary stochastic method **RSSIM (Carvalho et al. 2004)** and a new hybrid stochastic-deterministic approach, **DSM (Pacor et al., 2005)** are used in order to evaluate the ground shaking and to characterize its spatial variability.

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. Results are here presented and discussed in terms of PGA maps, for offshore and inland scenarios.


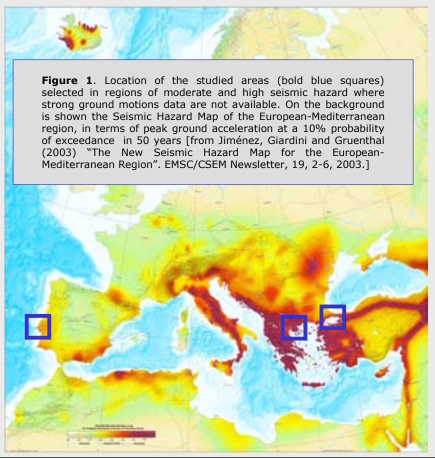

**Figure 1**. Location of the studied areas (bold blue squares) selected in regions of moderate and high seismic hazard where strong ground motions data are not available. On the background is shown the Seismic Hazard Map of the European-Mediterranean region, in terms of peak ground acceleration at a 10% probability of exceedance in 50 years [from Jiménez, Giardini and Gruenthal (2003) "The New Seismic Hazard Map for the European-Mediterranean Region". EMSC/CSEM Newsletter, 19, 2-6, 2003.]

**LESSLOSS Project: the Sub_Project 10 is devoted to do *"Disaster scenarios predictions and loss modelling for urban areas"*.**

**The shaking scenarios** (simulated response spectra; velocity/acceleration time series) **are evaluated** for three cities **Lisbon** (Portugal), **Thessaloniki** (Greece) and **Istanbul** (Turkey) using the **DSM** (Deterministic-Stochastic simulation Method), for all three cities, and **RSSIM** (Non-stationary stochastic Finite fault simulation Method), only for the Metropolitan Area of Lisbon (MAL). **The Loss modelling** of urban areas will be carried out using one of the two existing GIS-based software packages: the **KOERIloss** and the **LNECloss systems**.

**Note:** The program FINSIM has been also used to compare and calibrate both the program DSM and RSSIM. Some other analysis are on going to evaluate the dynamic corner frequency (EXSIM) and to produce simulations of Broad Band time series.

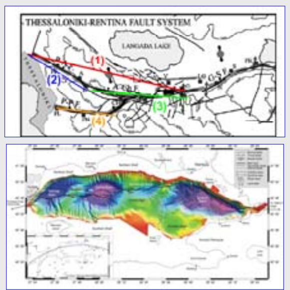

**Figure 2.** (from Spence et al., 2005) **Right Top:** The Thessaloniki area: we have hypothesized the rupture of four faults with magnitudes ranging from **M** 5.9 to 6.5 along the Thessaloniki - Gerakarou Fault Zone (TGFZ). **Right Bottom:** The seismic hazard in Istanbul is mainly associated within the Central Marmara Basin (CMB) and North Boundary Fault (NBF) active seismogenic areas. Two scenarios are considered: CMB-Scenario I, **M** 7.4 and NBF-Scenario II, **M** 6.9.

## The seismic risk of the Metropolitan Area of Lisbon

The seismic risk of the Metropolitan Area of Lisbon derives partly from offshore sources that cause large events, such as that which caused the catastrophic 1755 disaster, and was damaging over a very wide area; and partly from local sources that cause moderate earthquakes situated in or near the Metropolitan Area of Lisbon (MAL), such as the 1909 Benavente earthquake, which was locally destructive (see Figure 1). In the last decade of the XX century, MAL region suffered an intense construction rate; however, 27.3% of the existing buildings were constructed before the first Portuguese seismic code, enforce since 1960, and looking at Lisbon town this percentage raises to 63.9% (Campos Costa et al, 2002).

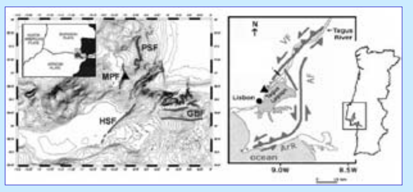

**Figure 1.** Left: Active faults in SW Iberia (modified from Matias et al., 2005). **MPF** – Marquês de Pombal Fault, **PSF** – Pereira de Sousa Fault, **HSF** – Horseshoe Fault, **GBF** – Guadalquivir Bank Faults. Triangle represents location of offshore scenario considered in this study. **Right:** Neotectonic of the Tagus Valley Region (modified Vilanova and Fonseca, 2004). **VF**- Vila Franca Fault, **ArR**- Arrábida range, **AF**- Alcochete fault. Triangle represents location of inland scenario considered in this study.

## The used inland and offshore seismic sources respect to the MAL

The earthquake scenarios computation requires first of all the evaluation of the most probable 50-year and 500-year earthquakes through seismotectonic studies and/or deaggregation of probabilistic seismic hazard analysis. The target earthquakes are defined by location, fault geometry, magnitude and other parameters, which are necessary to simulate the strong ground motion experienced at selected sites. There are mainly two seismic sources that could be critical for MAL and that are representative of short and long return periods, respectively: (a) the inland source area of Lower Tagus Valley (near Lisbon area) and (b) an offshore source area, probably associated to the 1755 Lisbon earthquake.

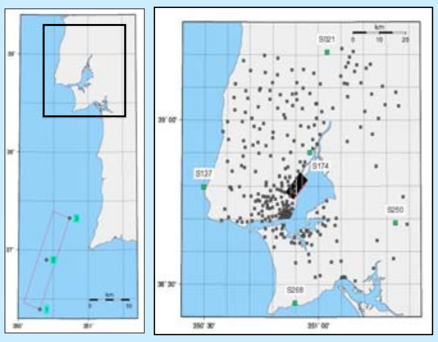

**Figure 2**. (from Zonno et al., 2005) **Left:** geometry of the offshore **MPTF** - Marques Pombal Thrust Fault **M** 7.6 respect to the MAL (black box). **Right:** the 276 MAL parishes (black dots) and the 5 test-parishes points S021, S268, S250, S137 and S174.

The assumed inland source LTVF - Lower Tagus Valley Fault **M** 5.7 is shown on the centre. We can see the different nucleation points of the fault LTVF MS.7 in Figure 4.

## The Finite-Fault Model Parameters

Finite-fault simulations require that the fault-plane geometry (length, width, strike and dip), the source parameters (seismic moment, slip distribution, stress drop, nucleation point, rupture velocity, etc.), the crustal properties of the region (geometrical spreading coefficient, quality factor, etc.) and the site-specific soil response information be previously specified. A dataset of digital acceleration records obtained from the Portuguese accelerometer network at hard-rock sites was employed to calibrate specific simulation parameters for RSSIM and DSM. The dataset includes events with moment magnitudes ranging from 4.1 to 5.3 and epicenter distances ranging from 15 to 320 km, for a total number of 11 events, with some event recorded at more than one site.

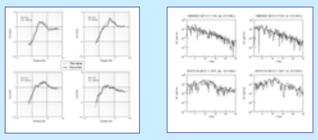

**Figure 3. Top left**: k estimations from the slope of the high frequency acceleration spectrum. WE and NS amplitude Fourier Spectra of the direct S wave pulse are shown in the left and right panels respectively. Top and bottom events refer to distances events of 15km and 35km, respectively. **Top Right**: example of response spectra comparison between synthetic and observed data. Up: intraplate events; down: interplate events. Circles give the simulated results. Lines are the response spectra computed from the observed horizontal components (solid: component N-S; dashed: component E-W).

Table 1. Geometry and dimension of the three considered seismic sources

| Sources | Offshore | Inland | Inland |
|---|---|---|---|
| Return period | 500 year | 500 year | 50 year |
| Moment 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 |
| Strike (degree) | 20 | 220 | 220 |
| Dip (degree) | 24 | 55 | 55 |
| Depth to upper edge of the fault | 4.5 km | 0.5 km | 2.0 km |

Table 2. RSSIM Fault Model Parameters for the interplate scenario

| | |
|---|---|
| Crustal thickness, D | 25 km |
| Quality factor, Q(f) | [illegible] |
| Geometric attenuation | [illegible] |
| Distance dependent duration | [illegible] |
| $f_{max}$ | [illegible] |
| Shear-wave velocity, β | [illegible] |
| Crustal density, ρ | [illegible] |
| Stress drop, Δσ | [illegible] |
| Amplification function | [illegible] |
| Number of subfaults along strike and dip | 20 x 5 |
| Slip model | [illegible] |

Table 3. DSM Fault Model Parameters for intra-plate scenario

| | |
|---|---|
| Crustal thickness, D | 25 km |
| Quality factor, Q(f) | [illegible] |
| Geometric attenuation | [illegible] |
| Distance dependent duration | [illegible] |
| κ | [illegible] |
| Shear-wave velocity, β | [illegible] |
| Crustal density, ρ | [illegible] |
| Number of subfaults along strike and dip | 20 x 10 |
| Slip model | Homogeneous |

**Tables on Right: Table 1.** Geometry and dimension of the three considered seismic sources; **Table 2.** RSSIM Fault Model Parameters for the interplate scenario and **Table 3.** DSM Fault Model Parameters for intra-plate scenario.

## The sensitivity analysis

To measure the sensitivity of different approaches (DSM, FINSIM and RSSIM) different nucleation points and rupture velocities (3 nucleation points, and for each, 3 rupture velocities) have been considered.

*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).*

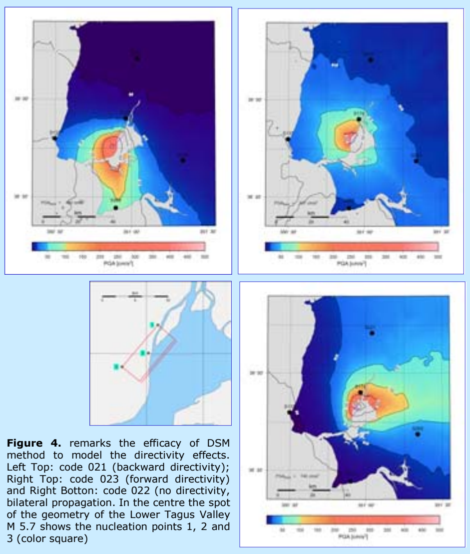

**Figure 4.** remarks the efficacy of DSM method to model the directivity effects. Left Top: code 021 (backward directivity); Right Top: code 023 (forward directivity) and Right Botton: code 022 (no directivity, bilateral propagation. In the centre the spot of the geometry of the Lower Tagus Valley M 5.7 shows the nucleation points 1, 2 and 3 (color square)

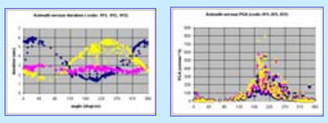

**Figure 5.** (from Spence et al., 2005) **Left:** the duration of the time histories as function of the azimuth. The centre of the **LTVF** is the origin and the azimuth is the angle of all 277 parishes in respect to the origin. **Right:** The values of PGA as function of the azimuth. The center of the LTVF is the origin and the azimuth is the angle of all 277 parishes in respect to the origin.

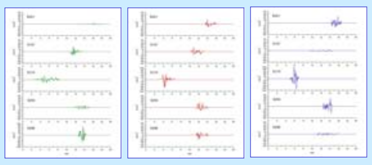

**Figure 6.** **DSM** method: simulation of time series component EW of LTVF **M** 5.7: **021** (green), **022** (red) **023** (blue)

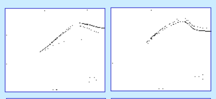

**Figure 7.** (from Carvalho et al., 2006) Comparison of response spectra PSA (5 % damping), for the S174 parish, for nucleation points 1 and 3 and velocity rupture of 2.5 km/sec. **Left:** DSM and FINSIM, for the inland **M** 5.7 scenario; **Right:** RSSIM and FINSIM, for the offshore **M** 7.6 scenario.

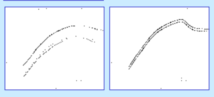

**Figure 8.** Sensitivity of response spectra to alternative: rupture velocities (2.5 km/sec and 2.9 km/sec) using the same nucleation point n.1. **Left:** DSM (codes 011 and 021) for the inland **M** 5.7 scenario; **Right:** RSSIM (codes 111 and 121), for the offshore **M** 7.6 scenario.

The figure 7 remarks the efficacy of DSM method to model the directivity effects. In fact at site S174, the parish closer to the LVTF, the PSA values obtained with code 011 (backward directivity) are much lower (by a factor about 2) than the ones computed with the code 013 (forward directivity). There is also some effect of directivity on the results of the classic FINSIM but only at higher frequency. PSA values estimated using DSM are much more sensitive to the rupture directivity than FINSIM.

## The evaluation of the seismic scenarios for the MAL

To evaluate the seismic scenarios for the inland source LTVF, response spectra have been produced for each parish of MAL based upon 30 trials for time histories using DSM and an average time duration. For the seismic scenarios performed for the offshore source MPTF we have computed directly response spectra at the bedrock using RSSIM.

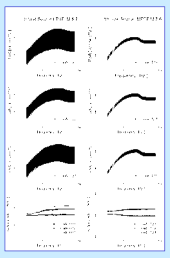

**Figure 9.** (from Carvalho et al., 2006) Response spectra, at bedrock, for all parishes of MAL, considering the nine scenarios performed using DSM for the inland source and RSSIM for the offshore source.

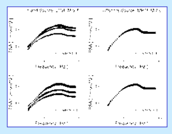

**Figure 10.** (from Carvalho et al., 2006) Fig. 8. Response spectra, at bedrock, for the S174 parish, considering the nine scenarios performed using DSM for the inland source and RSSIM for the offshore source.

**Note:** The figures 9 and 10 show the results considering the nine scenarios evaluated (3 nucleation points, and for each, 3 rupture velocities). As it is visible, the inland scenario presents a great scatter of results as the simulated ground motion has great variability between different inland scenarios, while for the offshore scenario there is no great sensitivity to the different models, due to the great distance between source and sites.

**PGA values obtained with DSM method** applied to the inland source LTVF M 5.7 is shown on the left side of Figure 9, for the three different nucleation points and considering a rupture velocity of 2.7 km/sec (J=2, in IJK scenario code). The directivity effects due to different rupture propagation on the fault are well marked: in the case 021 (top left) higher peak values are shown in the parishes located southern to the fault, as this case involves rupture towards these parishes, while in case 023 (bottom left) higher peak values are shown in parishes located northeastern to the fault, as in this case rupture propagates away from the southern parishes. The case of bilateral rupture (case 022) shows a radial pattern related to directivity.

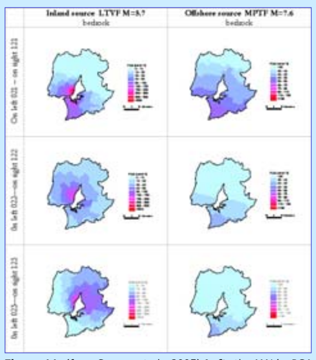

**Figure 11.** (from Spence et al., 2005) **Left:** the MAL' s PGA maps obtained with DSM method applied to the inland source LTVF **M** 5.7. **Right:** the MAL's PGA maps obtained with RSSIM method applied to the offshore source MPTF **M** 7.6. All the maps are relative alternative nucleation points: n.1, n.2 and n.3 (see Figure 4) with rupture velocity of 2.5 km/sec.

**PGA values obtained with RSSIM method** applied to the offshore source MPTF M 7.6 are illustrated on the right of Figure 9. For this far scenario, there is no spatial pattern related to directivity. For the three different ruptures, higher values are found in the southern parishes of MAL and lower values are found in the northern parishes. There is, however, a difference in peak values, higher peak values resulting from the scenario 121, meaning an upward propagation for all parishes, and lower values resulting from scenario 123, meaning a backward propagation, with longer duration.

**The simulated ground motion shaking** has great geographic variability. The range of values of each different nucleation point and the ratio values are synthesized in figure 9.

As it is shown, the inland scenario is very sensitive to directivity and has great scatter of peak values, PGA values varying from 10 cm/s2 in some parishes to 500 cm/s2 in others meaning that higher values are locally obtained and that seismic actions attenuates too fast with distance.

### The worst scenario

The worst scenario is defined considering, in each parish, the maximum value of shaking parameters of all scenarios. For 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.

The response spectrum of each parish was transformed into Power Spectrum Density Function (PSDF), at the bedrock, using the classical theory of stationary random process already described. Site effects were, then, evaluated following the numerical approach explained elsewhere in this paper and using an available data base, containing information on stratified soil profile units for MAL. Each soil unit considers the thickness of shallow layers, shear waves velocity, density and plastic index.

This data base was built in the framework of the project conducted by the Portuguese civil protection authority, for which it was conducted a geological - geotechnical survey that allowed the characterization of stratified soil profile units for MAL with a fair level of detail.

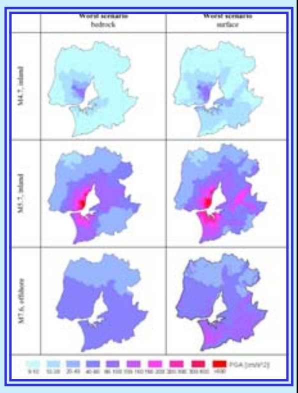

**Figure 12.** (from Carvalho et al., 2006) Worst scenarios of the Metropolitan Area of Lisbon (bedrock and surface) due to the inland and offshore sources.

# Numerical approaches

## The DSM synthesis

The **DSM** (Pacor et al., 2005) approach is a modification of the stochastic point source simulation method of Boore (Boore, 2003) which takes into account of finite fault effects, using synthetic acceleration envelopes computed by a simplified formulation of the isochron theory (Bernard and Madariaga, 1984; Spudich and Frazer, 1984).

Schematically, the synthesis of a time series is a four-step procedure consisting of:

1. Computation of the deterministic acceleration envelope of shear waves radiated from an extended fault.
2. Generation and windowing of the white noise time-sequence.
3. Introduction of the point-source-like reference spectrum.
4. Transformation back to the time domain.

The complex acceleration Fourier spectrum is transformed back to the time domain by an IFFT algorithm. Application of steps 1 to 4 implies that the resulting acceleration time series will show stochastic properties of the adopted Gaussian white noise and deterministic properties of the kinematic finite-fault source model employed to compute the acceleration envelopes.

## The RSSIM synthesis

The RSSIM (Carvalho et al., 2004) approach is a non-stationary stochastic simulation method that synthesizes the ground motion due to an extended source by means of an appropriate number of sub-sources, radiating as ω2 point sources. This method has been implemented starting from the classic simulation code FINSIM (Beresnev and Atkinson, 1998) widely employed in the seismological literature for simulation of the ground motion from both moderate and high magnitude earthquakes.

Like FINSIM, the RSSIM method assumes that the fault plane is a rectangle, subdivided into an appropriate number of sub-faults, which are modelled as point sources characterized by an ω2 spectrum.

Differently from FINSIM, RSSIM avoids the computation of acceleration time series representing the contribution of each sub-fault, but synthesizes the ground motion due to the entire fault from the Power Spectral Density Function (PSDF) radiated by each sub-fault, using the random vibration theory and the extreme values statistics.

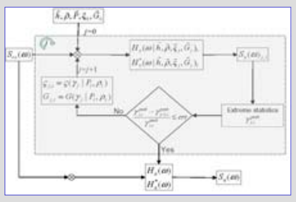

**Figure 14**. (from Carvalho et al., 2006) Iterative stochastic procedure adopted, for the consideration of the non-linearity of soil behavior. h, r, P, V, and G are initial values of soil layer parameters representing height, density, viscous damping ratio, plasticity index and elasticity distortion modulus, respectively. Sro(ω) represents the rock outcrop Power Spectral Density Function (PSDF) of acceleration, S$_j$(ω), i the PSDF at each iteration, j, for each stratified layer, i, and Sa(ω) the final PSDF at surface, considering the soil column unit effect. The same notation stands for the transfer function H(ω).

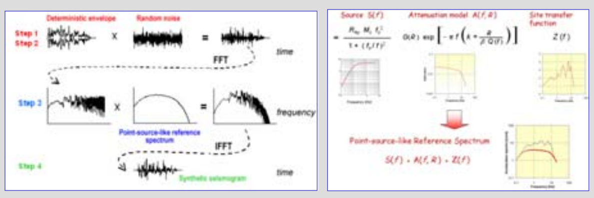

**Figure 13**. (from Spence et al., 2005) Left: scheme of DSM method: white noise windowed with the deterministic envelope (steps 1 and 2); FFT multiplied with a point-source-like amplitude spectrum (step 3); IFFT (step 4). Right: Point-source-like amplitude spectrum. The parameters of reference spectrum (i.e., corner frequency, distance from the fault, and radiation pattern) are evaluated through the kinematic model to capture the finite-fault effects. The other parameters, such as seismic moment Mo, spectral decay parameter k, quality factor Q, transfer function Z(f)) should be known.

The earthquake scenarios for each parish are defined by the computation of the Power Spectra Density Function (PSDF) of surface acceleration with due consideration of local site effects.

Both DSM and RSSIM output (time history and displacement response spectrum, respectively) must be quantified in terms of PSDF at bedrock. Once the displacement response spectrum has been achieved (directly from RSSIM and after FFT from DSM) the quantification of PSDF is performed through an iterative procedure, which is based on the possibility of computing the maximum values of the response spectrum, RS, from the power spectrum using an iterative procedure. To begin the iterative procedure values are chosen for the first PSDF. Then successive procedure cycles are carried out until a satisfactory approximation of the desire response spectrum is obtained (see Figure 14).

This approach allows a significant saving of calculation time, roughly a factor of twenty with respect to the usual approach based on the traditional methods, can be achieved.

## RESULTS and COMMENTS

- In this study we simulate the ground motion shaking in the city of Lisbon and surrounding counties (MAL - 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.
- Two numerical methods have been adopted for the prediction of strong ground motion of the Metropolitan Area of Lisbon due to extended faults: a hybrid stochastic-deterministic approach (DSM) and a non-stationary stochastic finite fault simulation method (RSSIM).
- The earthquake scenarios have been computed first at the bedrock sites. To include the local site effects, available microzonation studies have been used to characterize the site amplification. In the case of Lisbon, 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.
- A sensitivity analysis was carried out for different methodologies (DSM, RSSIM and FINSIM) and the variability of ground motion was studied. The variability of ground motion was studied from a set of fault ruptures scenarios incorporating different nucleation points and different ruptures velocities. The worst shaking scenarios for all the parishes of the Metropolitan Area of Lisbon have been delineated at the bedrock and surface level.
- Local effects amplify the synthetic PGA values by approximately a factor of 2. This means that PGA values computed for bedrock in Lisbon city can increase from 0.12g up to 0.25g and up to 0.5g in surroundings, for the inland scenario, and from 0.045g up to 0.090g for a M7.6 offshore scenario.

## MAIN OUTCOMES

The work presented in this poster forms a part of **SubProject 10 of the LESSLOSS Project**, "*Disaster scenarios predictions and loss modelling for urban areas*".

**The overall aim of SP10 is**: *"to create a methodology, based on state-of-the-art loss modelling 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"*.

- Following the purposes of the SP10 we have estimated ground motion scenarios in the frequency band of engineering interest (0.5-20 Hz) for the Metropolitan Area of Lisbon, that will be used for seismic loss estimate in urban areas.
- Following the purposes of the SP10 we have worked with existing methods and the GIS-based software as the LNECLoss system (Campos Costa et al., 2002) that comprises several modules to perform seismic risk analyses. The only two used modules concerning this study are the *Bedrock Seismic Input* and *Local Soil Effects evaluation*. An improvement of the LNECloss system will be possible incorporating the new approaches and all knowledge on sensitivity studies gained during the European Project LESSLOSS.

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**ACKNOWLEDGEMENTS**

*This study was funded by the European Commission through the **LESSLOSS** FP6 Integrated Project Risk Mitigation for Earthquakes and Landslides, No.: GOCE-CT-2003-505488.*