Simulating earthquake scenarios in the European LESSLOSS Project: the case of Lisbon

G. Zonno[1], A. Carvalho[2], G. Franceschina[1], A. Akinci[3], A. Campos Costa[2], E. Coelho[2], G. Cultrera[3], F. Pacor[1], V. Pessina[1], M. Cocco[3]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Milano - Pavia, Milan, Italy - Phone +39 02 23699286 Email zonno@mi.ingv.it*

[2] *National Laboratory for Civil Engineering, Structural Engineering Department, Lisbon, Portugal - Phone +351 21 8443291 Email xana.carvalho@lnec.pt*

[3] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Sismologia e Tettonofisica, Rome, Italy - Phone +39 06 51860401 Email cocco@ingv.it*

Abstract

Within the framework of the European LESSLOSS Project "Risk Mitigation for Earthquakes and Landslides", finite-fault seismological models have been proposed for the computation of earthquake scenarios for three urban areas: Istanbul (Turkey), Lisbon (Portugal) and Thessaloniki (Greece). For each case study, ground motion scenarios were developed for the two most probable events with different return periods (generally 50 and 500 years), locations and magnitudes that were derived from historical and geological data. The ground motion simulations were performed in the frequency band of engineering interest (0.5-20 Hz) by two numerical finite-fault methods: a hybrid deterministic-stochastic method, DSM, used for all of the cases investigated, and a non-stationary stochastic finite-fault simulation method, RSSIM, applied only in the case of Lisbon.

In the present study, the results with respect to bedrock and surface are presented in terms of peak ground acceleration (PGA) for the city of Lisbon and the surrounding area, using earthquake scenarios from the onshore source area of the Lower Tagus Valley, and from the offshore source area of the Marques de Pombal fault, which is one of the possible sources of the 1755 Lisbon earthquake. Site effects are evaluated by means of a properly designed equivalent stochastic non-linear one-dimensional ground response analyses of stratified soil profile units. The requirements of the users (e.g., engineers, local administrators) constrain the choice of the scenario that can be adopted as input for disaster scenario predictions and loss modelling; in the case of Lisbon, the maximum values of shaking were assumed as the criteria for the reference scenarios.

Introduction

This study is a continuation from our previous study published in the Proceeding of the 1755 Lisbon Earthquake Conference [Zonno et al., 2005] and it contains the main results following from the European LESSLOSS Project "Risk Mitigation for Earthquakes and Landslides" [Lessloss, 2004], regarding the evaluation of earthquake scenarios for the metropolitan area of Lisbon (MAL).

In the framework of subproject 10, SP10, "Earthquake disaster scenario prediction and loss modelling", finite-fault seismological models have been proposed for the computation of earthquake scenarios for three urban areas: Istanbul (Turkey), Lisbon (Portugal) and Thessaloniki (Greece). The overall aim of SP10 is to create a tool that is based on state-of-the-art modelling software and that provides strong quantified statements about the benefits and costs of a range of possible mitigation actions, to support the decision making by city and regional authorities towards seismic risk-mitigation strategies [Spence, 2007]. The first element of this analysis process is the definition of the input in terms of hazard parameters [Figure 1].

Fig. 1

The generation of earthquake ground motion scenarios involves both the particular choice of earthquake sources with the associated fault rupture parameters, and the ensuing ground motion field, calculated using an appropriate numerical tool, or empirically estimated at a set of selected points within the urban area of interest. For SP10, the aim was to define the ground shaking hazard associated with particular scenarios, which were defined as earthquakes with a given magnitude and location, and were taken to be the worst event scenarios which would take place with a given return period, of 50, 100 or 500 years [Cornell, 1968]. Defining such earthquakes requires a close study of the faults involved and of the earthquake recurrence on those faults, and it may also require a de-aggregation analysis of the effects from all of the faults that can generate damaging ground motions at a specific site [Bazzurro and Cornell, 1999].

Approaches to ground shaking hazard depend on the type and level of the analysis to be undertaken. In the presented case specific parameters of surface ground motion are needed as inputs towards the structural vulnerability, and these are derived from a two-step process. In the first step, a set of expected bedrock ground motions are determined. This is obtained either by the use of empirical ground motion attenuation relationships, or

with greater sophistication by the use of simulation techniques in which the mechanics of ground motion transmission from source to site is simulated. In the second step the bedrock ground motion is used to determine the expected surface ground motion, based on an understanding of the typical soil profile at each location. Again, this can be achieved in different ways: either using dynamic soil-column analysis, or using standard soil amplification coefficients that are applicable to the given soil type and depth.

Definition of scenario earthquakes

Probabilistic seismic hazard analysis (PSHA) carries out integration over the contributions to the hazard from all of the sources within a region, for certain ranges of magnitude, M, and distances, R. It provides an estimation of a strong-motion parameter with a specified confidence level, during a given exposure period. Moreover, it can account for the uncertainties that are associated with the estimation of the seismicity and of the attenuation characteristics of the region. This latter property is taken into account by an additional integration over a given number of standard deviations, ε , of the adopted ground motion attenuation law [Cornell, 1968; Bazzurro and Cornell, 1999].

Because of its integrative nature, PSHA does not provide a representative earthquake that can be used for engineering analyses and decision making, in terms of magnitude and source-to-site distance. However, this can be achieved through the de-aggregation of the PSHA results. The fundamental objective of this analysis is to compute the contribution to the hazard at a specific site of every possible source, S= (M,R, ε), considered in the composite PSHA calculations. This allows for a “controlling” earthquake, in terms of the magnitude M and the source-to-site distance R or the geographical coordinates, and for the identification of the location of the most probable source that contributes to the hazard at a well-defined site. The measure of the deviation of the ground motion from the predicted value, ε , can also be considered in the de-aggregation process. Information about the “controlling” source can be used to generate a scenario earthquake, which is the basis of the deterministic hazard assessment [Harmsen, 2001; Harmsen and Frankel, 2001]. Because deterministic scenarios are associated with representative earthquakes, they can be performed by advanced ground motion simulation methods that allow the reproduction of specific source effects, like the extended fault properties, the earthquake rupture propagation, and the asperity distribution on the fault plane. It is of note that if the seismic source is accounted for by only the magnitude and distance parameters, none of these effects are considered.

Evaluation of seismic scenarios

The first important distinction between the recommended approaches for creating ground shaking scenarios is for simplified or advanced methods. Simplified methods make use of empirical attenuation relationships of ground motion parameters and local geological data. Within the LESSLOSS Project, advanced methods are applied extensively because they can physically represent the ground motion. Indeed, finite-fault effects and directivity can assume very important roles. Moreover, the high resolution of ground motion scenarios can match the complexity of the geotechnical characterization, vulnerability data and exposure factors that are involved in the urban level loss estimations.

For the earthquake scenarios, the earthquake source locations, its geometrical and kinematic structure, and the starting point of the fault rupture are very important issues. Therefore, the finite-fault simulations require specification of the fault-plane geometry (length, width, strike, dip, number of sub-faults considered, and depth to the upper edge), source (stress drop, seismic moment, slip distribution, nucleation point, rupture velocity) and the crustal properties of the region (geometric spreading coefficient and quality factor) and the site-specific soil response information. The fault dimensions as a function of the moment magnitude can be calculated using empirical relationships [e.g. Wells and Coppersmith, 1994].

Numerical approaches

Ground motion simulations were performed in the frequency band of engineering interest (0.5-20 Hz) by two numerical methods: a hybrid deterministic-stochastic method DSM [Pacor et al., 2005], which is used for all of the cases investigated, and a non-stationary stochastic finite-fault simulation method RSSIM [Carvalho et al., 2004], which is only applied in the case of Lisbon. Both methods allow the computing of the synthetic ground motion for direct S-wave fields at bedrock sites, and are suitable for the generation of 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.

Different rupture propagation models based on the selected faults can be hypothesized, and even when input data regarding the earthquake source, propagation medium and site characteristics are of a very schematic nature, the

complexity of the near-source ground motion can be adequately reproduced. Extended fault simulations performed with different earthquake rupture models generally produce high variability in the ground motion, which is mainly dependent on the assumed position of the hypocenter on the fault plane that controls the rupture directivity.

During the LESSLOSS Project, a sensitivity study was performed using different input parameters and different approaches in order to provide the basic information for the evaluation of the range of uncertainty in the seismic scenarios. In the case of Lisbon, this analysis was carried out by comparing DSM and RSSIM results with simulations obtained by FINSIM [Beresnev and Atkinson, 1998] considered as a reference and a worldwide known tool.

The case of Lisbon

Historically, the MAL has been struck by infrequent, though intense, earthquakes, such as the 1755 Lisbon earthquake that was estimated at magnitude **M** 8.7. The earthquake scenarios were defined based on de-aggregation of the PSHA for different return periods [Campos Costa et al., 2002; 2006], which allowed the independent assessment of the offshore and inland seismic sources [Figure 2]. Based on the revised de-aggregation of the PSHA [Sousa, 2006], it was possible to conclude that the seismic hazard in the MAL is dominated by long distance scenarios (offshore sources), for return periods greater than 50 years with magnitude **M** 7.9. The most recent studies on tectonic structures that could be associated with the 1755 Lisbon earthquake were used to define plausible parameters for the simulation of the offshore sources, while seismotectonic studies on the Lower Tagus Valley were used to define the simulation parameters of the inland sources [Baptista et al., 2003; Cabral et al., 2004].

On the basis of the revised de-aggregation analyses [Sousa, 2006], the seismic action scenarios presented in Zonno et al. [2005] were updated. The revised scenario, corresponding to 500-year return period, is still located offshore, validating the preliminarily conclusions relating to the spatial variability of the ground shaking in the MAL. Instead, for the 50-year return period, the de-

aggregation analysis indicates a new short distance scenario that corresponds to inland sources of magnitude **M** 4.4. The corresponding source was located beneath the Lower Tagus Valley, on the east side of the MAL, and from previous studies it is possible to infer both the geometrical parameters and the focal mechanism for a plausible source [Cabral et al., 2004].

Following this revised methodology, the dominant scenarios found for Lisbon city are presented in Figure 2 and the fault geometry and the source mechanisms are given in Table 1.

Fig. 2

The model parameter calibration has been carried out with a dataset that includes the horizontal components of ground acceleration records (hard sites) obtained by the national digital accelerometer network of Lisbon [Carvalho et al., 2005]. The other parameters, including the crustal properties and the source calibration parameters for the completion of the finite-fault simulation have been defined in previous studies [Zonno et al., 2005; Carvalho et al., 2007].

Table 1 Fault parameters of the seismic sources used to perform the finite-fault simulations in the case study of Lisbon.

Table 1

In this study we present a bedrock ground motion simulation of the acceleration for Scenario II obtained by DSM [Pacor et al., 2005] and both bedrock and surface simulation for Scenario V obtained by RSSIM [Carvalho et al., 2004] (see Table 1).

Evaluation of seismic scenarios: onshore analysis

The ground motion was computed at the bedrock level through extended fault simulations, and then modified by considering the site effects. The characterization of local soil effects was taken into account by computing the PSDF at the surface level and considering for each parish the non-linear behaviour of the stratified geotechnical soil profile that was available.

Fig. 3

Figure 3 shows the PGA grided maps obtained in the MAL through the DSM extended fault simulations using the M 5.7 inland source (the Lower Tagus Valley fault) and three nucleation points (NE/SW unilateral (1), bilateral (2) and SW/NE unilateral (3) rupture). As can be seen, the unilateral rupture propagation (cases 1 and 3) produce the greatest variability in the ground motion. The sites experiencing forward directivity (located South and East of the source in cases 1 and 3, respectively) are characterized by large amplitudes (and short duration). The bilateral case shows an almost radial distribution of the PGA around the fault.

Fig. 4

In Figure 4, the DSM time series acceleration obtained at two test sites (Figure 2, S174 and S268) in the MAL are shown for the inland source of **M** 5.7 for the three different rupture models, with a velocity rupture of 2.7 km/s. The PGA variability is due to uncertainties in both the nucleation point position and the rupture velocity, and it is generally present over the entire simulated frequency band (f > 1 Hz).

Both Figures 3 and 4 show that the ground shaking scenarios obtained through extended fault simulations had high variabilities, which were mainly due to directivity effects. Indeed, ground motion maps are very sensitive to the position of the nucleation point on the fault plane, and unfortunately this is probably the most uncertain seismological information that we have to introduce into simulations. Nevertheless, extended fault simulations are needed to properly reproduce the earthquake ground motion from large and/or near sources.

Evaluation of seismic scenarios: offshore analysis

Offshore analysis was carried out previously using the RSSIM method and different slip distributions [Zonno et al., 2005]. More recently [Spence, 2007], the RSSIM simulation of the at sites located on the Portuguese mainland for earthquakes generated offshore, considering a wide range of magnitudes and

distances, allows estimating a regional ground motion attenuation law. The PGA maps for offshore scenarios [Figure 5] were then computed using the obtained attenuation law for rock sites and taking into account the site effects by means of an equivalent stochastic non-linear one-dimensional ground response analysis of stratified soil profiles using the LNECloss system [Sousa et al., 2004; Serra and Caldeira, 1998].

The ground motion maps presented here show higher values of PGA in comparison with the acceleration maps obtained in the initial analysis [Zonno et al., 2005]. Moreover, Figure 5 (right) reveals that the non-linear soil amplification is quite pronounced, particularly in the southern margin of the Tagus River, where the soft soil sites are laid over bedrock (in this area, the peak ground accelerations range between 250 and 300 gal).

Fig.5

Conclusions

From the seismological point of view, many equally probable ground shaking scenarios were simulated while varying the nucleation point over the fault plane, the rupture propagation velocity and the slip distribution. The following criteria can be used in making the final choice:

- the proposed scenarios are those more compatible with the standard PSHA analysis of the hazard in terms of the peak values of strong ground motion parameters and spectral ordinates;
- according to the final application, either the mean or the worst-case scenarios could be used. The choice depends on the demand of the local administrators, the sensitivity to the earthquake phenomena, and above all, the level of seismicity in the area.

ACKNOWLEDGMENTS

This study was performed with the financial support of the European Commission through the LESSLOSS FP6 Integrated Project Risk Mitigation for Earthquakes and Landslides, No.: GOCE-CT-2003-505488.

REFERENCE

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 modelling" Natural Hazards and Earth System Sciences, 3, pp. 333-340.

Bazzurro, P., Cornell, C. A. (1999). "Deaggregation of Seismic Hazard", Bull. Seism. Soc. Am., 89, 501-520.

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.

Campos Costa A, Sousa M. L, Carvalho. A., Bilé Serra J., Carvalho E. C. (2002). "Regional Seismic Risk Scenarios on hazard deaggregation", Proceedings, 12th European Conference on Earthquake Engineering, London, paper 470.

Campos Costa, A., Sousa, M. L., Carvalho, A., Coelho, E. (2006). "Seismic loss scenarios based on hazard de-aggregation. Application to the Metropolitan Region of Lisbon, Portugal", Chapter 21 in the book Assessing and Managing Earthquake Risk, Editors: C.S. Oliveira, A. Roca and X. Goula, publisher: Kluwer.

Cabral, J., Ribeiro, P., Figueiredo, P., Pimentel, N., Martins, A. (2004). "The Azambuja fault: An active structure located in an intraplate basin with significant seismicity (Lower Tagus Valley, Portugal)", Journal of Seismology , 8, pp. 347–362.

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. & Oliveira, C. S. (2005). "A Finite-fault modeling of the 1755 Lisbon earthquake sources", Proceedings International Conference 250th Anniversary of the 1755 Lisbon Earthquake, Lisbon. pp 578 – 583.

Carvalho, A, Zonno G, Franceschina G, Bilé Serra J, and Campos Costa A (2007). "Earthquake shaking scenarios for the Metropolitan Area of Lisbon", Soil Dynamics and Earthquake Engineering, accepted for publication.

Cornell, C. A. (1968). "Engineering seismic risk analysis", Bull. Seism. Soc. Am., 58, pp. 1583-1606.

Harmsen, S.C., Frankel, A. (2001). "Geographic Deaggregation of Seismic Hazard in the United States", Bull. Seism. Soc. Am., 91, 13-26.

Harmsen, S.C. (2001). "Mean and Modal in the Deaggregation of Probabilistic Ground Motion", Bull. Seism. Soc. Am., 91, 1537-1552.

Lessloss (2004) http://www.lessloss.org/

Spence R. (editor) (2007). "Earthquake Scenarios, Loss Modelling and Mitigation for Urban Areas", Dissemination report SP10 - LessLoss Project: Risk Mitigation for Earthquakes and Landslides Integrated Project, Sixth Framework Programme Project No.: GOCE-CT-2003-505488, June, 191 pp.

Pacor, F., Cultrera, G., Mendez, A. , Cocco, M. (2005). "Finite Fault Modeling of Strong Ground Motion Using a Hybrid Deterministic - Stochastic Method," Bull. Seism. Soc. Am., 95, 225-240.

Serra, Bilé, J., Caldeira (1998). "Dynamic behaviour of geotechnical structures by means of a stochastic approach", conference Applications of Computational Mechanics in Geotechnical Engineering, Portugal.

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 Paper No. 2526.

Sousa, M.L. (2006) "Risco sísmico em Portugal Continental", PhD thesis, IST, Lisboa.

SNPC (2003). “Caracterização, Vulnerabilidade e Estabelecimento de Danos para o Planeamento de Emergência sobre o Risco Sísmico na Área Metropolitana de Lisboa e nos Municípios de Benavente, Salvaterra de Magos, Cartaxo, Alenquer, Sobral de Monte Agraço, Arruda dos Vinhos e Torres Vedras, Contribuição para uma Simulação Simplificada de Danos”, Relatório final, Report 280/02, 2002; G3ES, Proc. 037/1/13810, LNEC (in Portuguese).

Wells, D.L., Coppersmith, K.J. (1994). “New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement”, Bull. Seism. Soc. Am., 84, pp. 974-1002.

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)”, “250th anniversary of the 1755 Lisbon earthquake”, 1-4 November 2005, Portugal.

FIGURE CAPTIONS

Figure 1. Schematic procedures for the ground motion simulations for Lisbon, in the framework of the LESSLOSS Project.

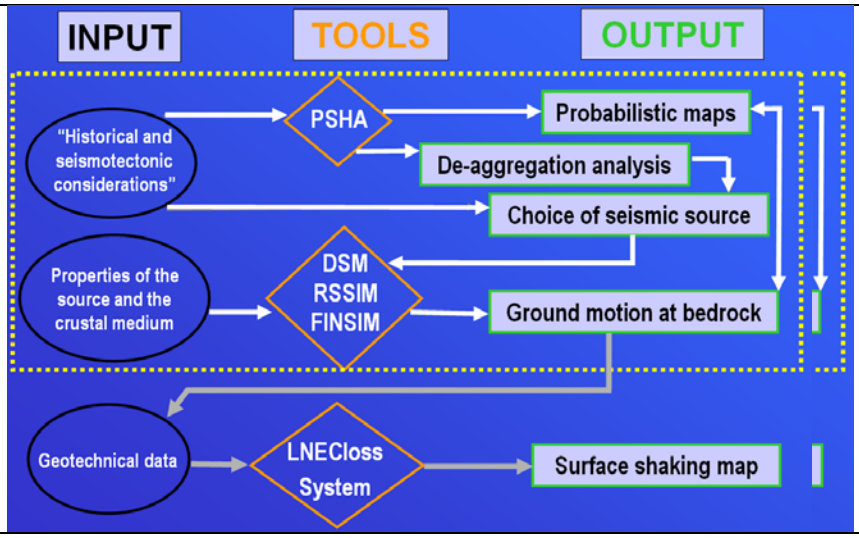
Figure 2. Surface projections of the faults presented in Table 1. Left: position of the offshore sources MPTF **M** 7.6 and MPTF **M** 7.9 with respect to the MAL (black box). Right: position of the inland sources LTVF **M** 5.7 and LTVF **M** 4.4 (black box and black circle, respectively). A spot of the LTVF **M** 5.7 source with the assumed nucleation points is shown to the top left. The 277 parishes where the synthetic time series were computed are also shown (small black squares), together with the five test parishes selected for the sensitivity analysis (sites S021, S268, S250, S137 and S174).

Figure 3. PGA maps obtained in the MAL through extended fault simulations using the M 5.7 inland source (Lower Tagus Valley fault). Nucleation points of the NE/SW unilateral (1), bilateral (2) and SW/NE unilateral (3) rupture propagations are indicated in the box at the bottom right, together with the surface projection of the fault. The rupture velocity V_R = 2.7 km/s was adopted for all of the cases.

Figure 4. DSM acceleration time series obtained at the two test sites (Figure 2, S174 and S268) in the MAL for the inland source of **M** 5.7, with different rupture models. Left panel: unilateral nucleation (NE/SW, green lines; SW/NE, blue lines) and bilateral nucleation (red lines).

Figure 5. PGA maps for the MAL obtained at the bedrock (left) and surface (right) levels for the **M** 7.9 offshore source scenario, with a 500-year return.

Fig.1


INPUT
TOOLS
OUTPUT
"Historical and seismotectonic considerations"
PSHA
Probabilistic maps
De-aggregation analysis
Choice of seismic source
Properties of the source and the crustal medium
DSM
RSSIM
FINSIM
Ground motion at bedrock
Geotechnical data
LNECloss System
Surface shaking map

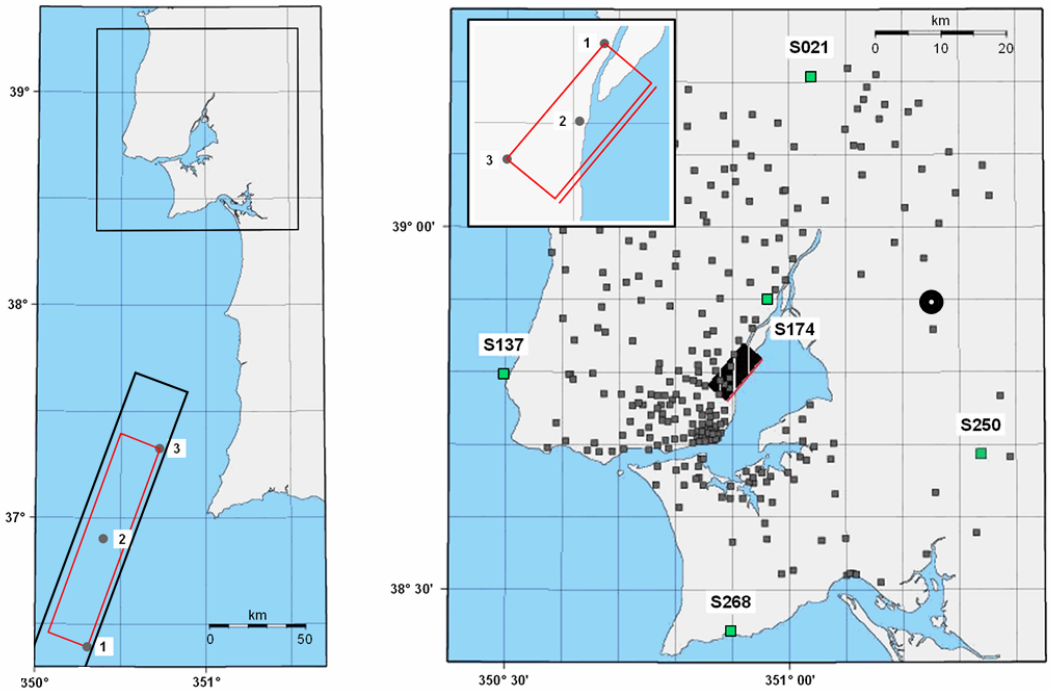

39°
38°
37°
350°
351°
km
0
50
1
2
3
39° 00'
38° 30'
350° 30'
351° 00'
km
0
10
20
S021
S174
S137
S250
S268

Fig. 2

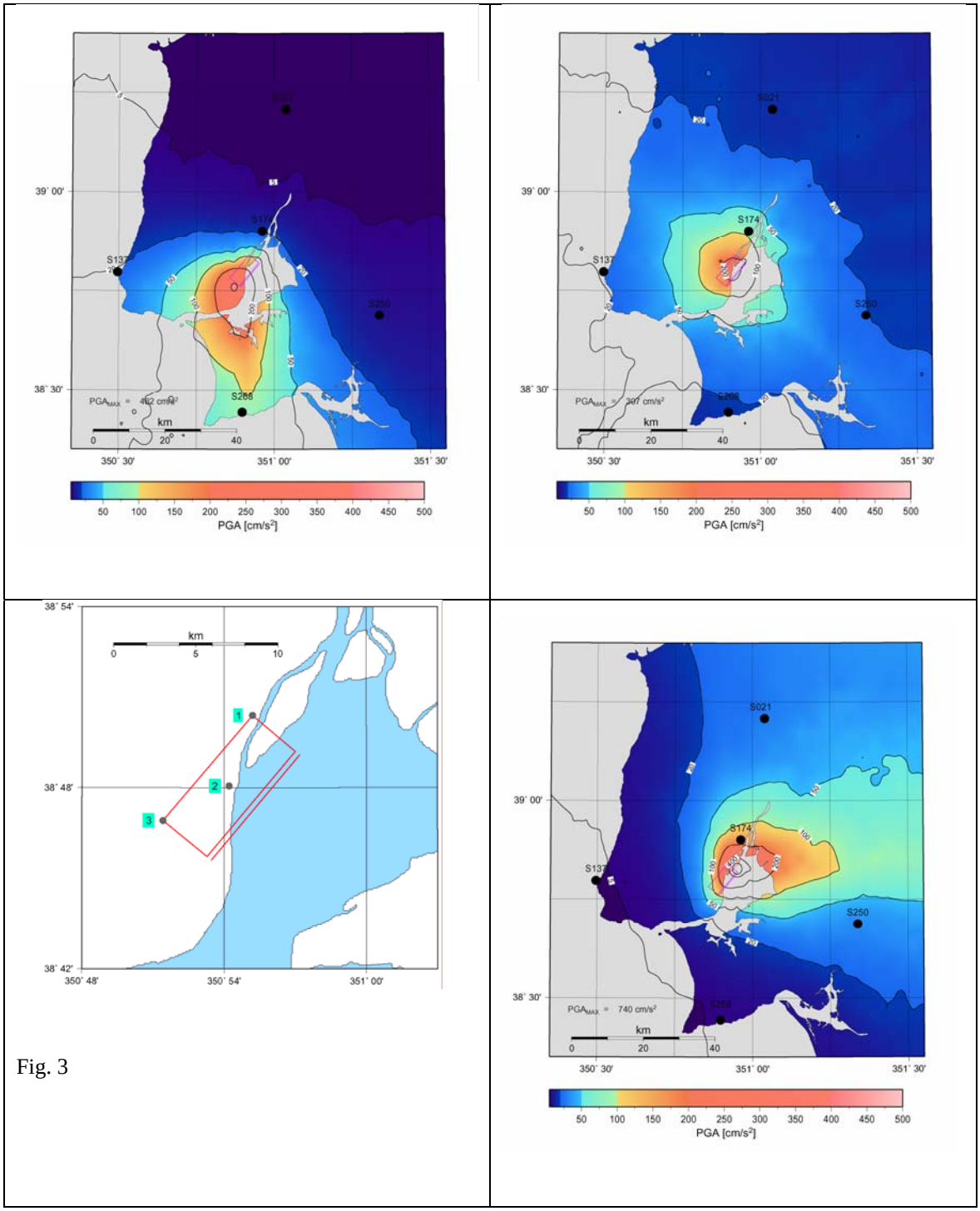

39° 00'
38° 30'
S137
S174
S250
S268
PGA_MAX = 412 cm/s²
km
0
20
40
350° 30'
351° 00'
351° 30'
50 100 150 200 250 300 350 400 450 500
PGA [cm/s²]
S021
PGA_MAX = 307 cm/s²
PGA_MAX = 740 cm/s²
38° 54'
38° 48'
38° 42'
350° 48'
350° 54'
351° 00'
km
0
5
10
1
2
3

Fig. 3

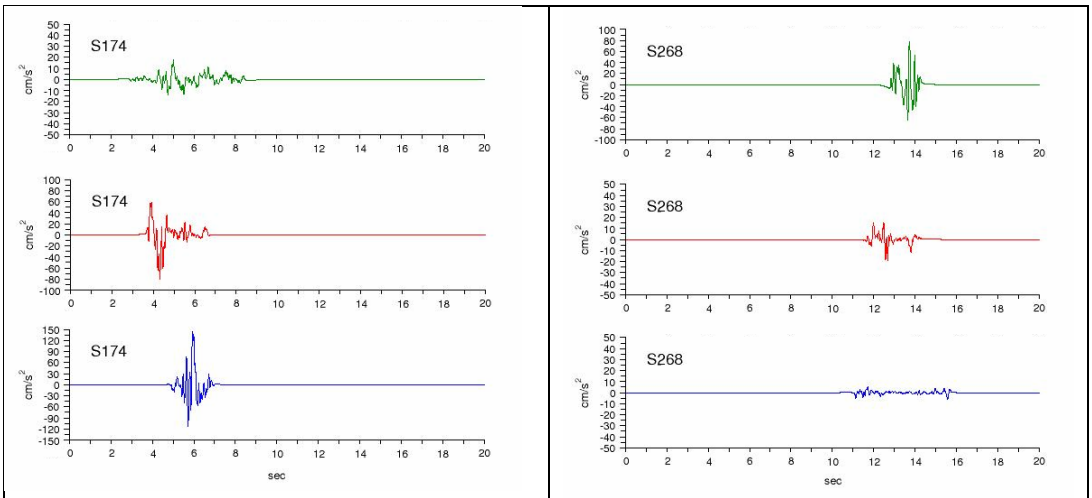


Fig.4

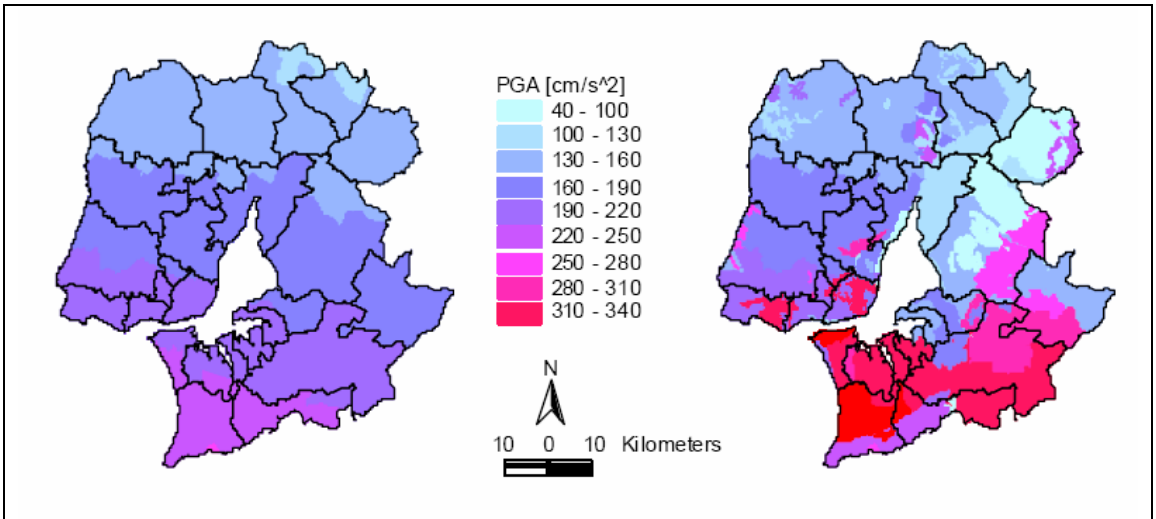


Fig. 5

Table 1

Name of seismic scenario	Fault Name	Mw	Return period (year)	Length (km) x Width (km)	Dip (degree)	Strike (degree)	Ztop (km)
Scenario I	LTVF	4.4	50	1.4 x 2.3	55	220	0.5
Scenario II	LTVF	4.7	75	2.2 x 2.8	55	220	2.0
Scenario III	LTVF	5.7	200	8.4 x 6.0	55	220	0.5
Scenario IV	MPTF	7.6	200	110 x 24	24	20	4.5
Scenario V	MPTF	7.9	500	166 x 30	24	20	4.5