Seismic Scenario Simulations Using a GIS Web Service

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ABSTRACT

Throughout its history, Portugal Mainland and Azores Archipelago have suffered the catastrophic effects of earthquakes originating significant damages in buildings and human losses. Being aware of Portuguese seismic risk, civil protection authorities promoted some studies leading to the development of a seismic scenario simulation tool, applicable to some Mainland Portuguese regions.

This paper describes recent improvements in the seismic scenario simulation tool, named LNECloss, and illustrates its applications to the evaluation of building damages and social losses, due to plausible seismic scenarios affecting Portugal.

Some development requirements were identified in LNECloss simulator, namely making it available as a service on the Web, providing a stand alone tool, with no need of a geographic information desktop environment, although with the GIS capabilities of mapping and synthesis of the seismic scenario effects.

In conclusion, the developed GIS Web Service offers a useful tool for seismic risk assessment and emergency planning and management.

Keywords

Portugal, seismic scenarios, simulator, Web service, seismic risk.

INTRODUCTION

LNECloss is a computer tool that evaluates losses as a consequence of user defined ground motion seismic scenarios. This tool comprises several modules like the modelling of seismic action at bedrock and at surface level, the evaluation of earthquake damage to buildings and the estimation of human and economic losses. The main core simulator was developed in a scientific programming language (FORTRAN 90), which was integrated, as an external application, in a Geographic Information System (GIS).

LNECloss have been developed and updated in the framework of previous projects (Campos Costa, Sousa, Carvalho, Bilé Serra, Martins. and Carvalho; 2004; LESSLOSS, 2007; Sousa, Campos Costa, Carvalho and Coelho, 2004; Sousa, Carvalho, Bilé Serra and Martins, 2010). LNECloss was initially designed to be a tool for supporting the Civil Protection seismic risk emergency plan for the Metropolitan Area of Lisbon and nearby counties. Lisbon is the main and major city of Portugal, and its urban region has the highest seismic risk in the country. Soon after, within the scope of European and Portuguese research projects, LNECloss was updated to estimate the seismic risk in other regions and to identify earthquake protection strategies in order to reduce future losses (Sousa et al., 2010). In the framework of the USuET project (*Urban System under earthquake threat: An integrated global approach. Application to the Azores*), this modeling tool was also updated aiming at extending its geographic domain of application to the Azores archipelago, as this is the Portuguese region with the highest seismic rate (Sousa and Afonso, 2008). Additionally, under a collaborative project entitled

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Seismic and Tsunami Risk Study for Algarve (ERSTA – *Estudo do Risco Sísmico e de Tsunamis do Algarve*), supported by the Portuguese National Authority for Civil Protection (ANPC), the simulated effects of several seismic scenarios were analyzed in the Algarve region. Actually, Algarve is one of the Portuguese regions that most suffered with the occurrence of destructive seismic events, namely the 1755 earthquake and its tsunami, so crisis management authorities promoted some studies intending to support, scientifically, the seismic risk emergency plan for the region (Sousa *et al.*, 2010).

Furthermore, the seismic scenario simulator was brought up-to-date to a GIS Web service in order to develop a stand alone tool, with no need of a geographic information desktop environment, although with the GIS capabilities of mapping and synthesising the seismic scenario effects. This updated simulator provides a Web service tool that can support decision makers on emergency management and planning, associated to seismic disasters occurring in any parish of Mainland Portugal and Azores islands. A useful graphic interface might potentiate its operation by civil protection agents for planning and managing a seismic disaster emergency.

BUILDING DAMAGES AND HUMAN LOSSES MODELS

Building damage model

LNECloss uses the capacity spectrum method (ATC, 1996), broaden worldwide by the HAZUS loss estimation methodology (FEMA and NIBS, 1999), to evaluate the peak response for each building type, referred as the performance point. The evaluation of peak response relies on the intersection of its capacity curve with the seismic spectral demand at the site. The initial elastic response spectrum is iteratively reduced to the so called demand spectra, considering building degradation when exposed to seismic motion. The procedure is illustrated in Figure 1 (Campos Costa, Sousa, Carvalho and Coelho, 2010). The abscissa of this performance point describes the effect of seismic action, measured in terms of spectral displacement, *SD*. This value conditions the cumulative lognormal probability distributions of the variable damage, $\mathrm{P}_D(d)$ that model building fragility:

$$\mathrm{P}_D\left(D \geq d \,\middle|\, SD\right) = \Phi\left[\frac{1}{\beta_d}\ln\left(\frac{SD}{\overline{SD_d}}\right)\right] \tag{1}$$

Building fragility curves allow the evaluation of the probability to exceed the threshold of a given damage state, conditioned by the level of seismic ground motion, *SD*, where Φ is the standard normal cumulative distribution function, $\overline{SD_d}$ is the median of spectral displacement at which the building reaches the threshold of the damage state *d*; β_d is the standard deviation of the natural logarithm of spectral displacement of the damage state *d*. Five damage states were considered that are dependent on the analyzed typology: «No damage», «Slight», «Moderate», «Severe» and «Total Damage». Approximately 10 to 25% of the total area of the buildings in «Total Damage» state is likely to collapse totally, whereas the remaining is expected to collapse partially (LESSLOSS, 2007). The threshold of those damage states are established in terms of global drift for each building typology.

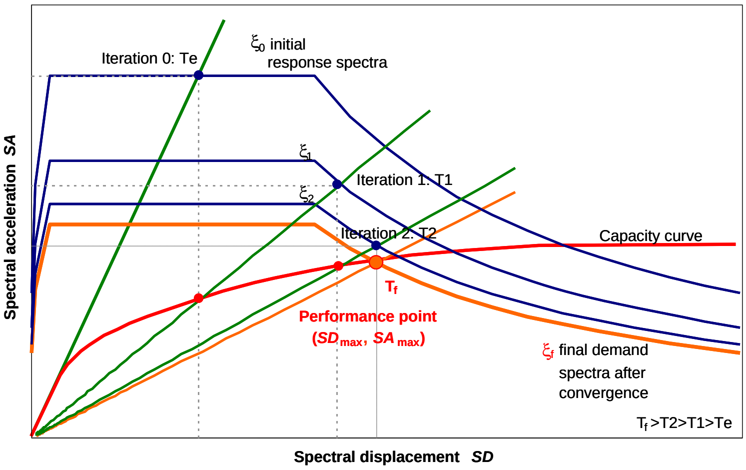

Figure 1. Iterative process to obtain the building response peak in the framework of the capacity spectrum method (Campos Costa *et al.*, 2010)

Human losses model

LNECloss estimates human casualties and other direct social losses caused by building damages, considering building damage state and occupancy per typology. Human casualties' matches to the expected number of dead occupants or in different injured severity levels, estimated by FEMA and NIBS (1999) and Coburn and Spence (2002) methodologies. Casualty rates of these methodologies were adapted to the Portuguese situation. Direct social losses evaluation include the estimation of displaced households, due to the loss of housing habitability, following the worldwide applied methodology FEMA and NIBS (1999). Briefly, this methodology estimates the number of uninhabitable dwelling units, considering that two main reasons might contribute to people leave their homes: (i) building structural damages and (ii) loss of utilities induced, for instance, by damages in power and/or water lifelines.

SEISMIC SCENARIO SIMULATOR LNECloss AS A GIS WEB SERVICE

Architecture and technologies used

The availability of GIS tools through the Web, handles a very specific architecture. The LNECloss Web service architecture is based, generally, in a *three-tier* Client/Server model, where has been adopted a Server-Side strategy, which allows the users to make their analysis requests to a Web Server. It processes all operations, sending back the results to the user, who may see them in a Web browser (Peng and Tsou, 2003).

The development of the Simulator, LNECloss, in a GIS Web service, was conceived and implemented in a Linux environment (*Red Hat Enterprise v. 5.0*) using mainly the Java language for the main core programming. Java language was chosen because, above all, it is a transversal technology across operating systems that allow the portability of the application between different environments (Sousa, Afonso and Matos, 2008a).

As referred previously, it was implemented the *three-tier* architecture for the development of the Simulator LNECloss as a Web service. Three main tiers constitute this type of structure: (i) *Presentation-tier*, (ii) *Middleware* (Web Server and GIS Application Server), and (iii) *Database-tier* (Peng and Tsou, 2003).

Presentation-tier

Several Graphic User Interfaces (GUI's) were designed, in the framework of the *Presentation-tier*, with the main purpose of accepting user requests to trigger Simulator operations. The user must choose scenarios characteristics and modeling options, which will condition the type of output maps, the global statistics for the chosen scenario and the final results. The GUI's are composed by a set of forms made available through a set of hyper connections with different functionalities. The GUI's were implemented using technologies like, *HTML* (Hyper Text Markup Language), *JSP* (Java Server Pages) and *Javascript* routines.

Middleware

A Web Server and a GIS Application Server constitute the *Middleware* and make the Web service available. The Web Server's technology was based on the *Apache Tomcat* (developed under *Jakarta Project* on the *Apache Software Foundation*) that is an open-source Web Server, which uses Java technology. Concerning the GIS Application Server, it was based on the ArcIMS™ technology by ESRI®. The ArcIMS package consists in a map service platform that makes spatial data available on the Web. This technology uses a Spatial Server that communicates with the Web Server through an Application Server Connector (in this case a *Java Connector*), using ArcXML language, which is a XML specification that assures the communication and the creation of structured messages between the Web Server and the GIS Application Server, in order to reply to the client requests.

Database-tier

Concerning the *Database-tier*, it manages the simulations results that are contained in a set of text files. The production of these files is preceded by the user requests and consequent triggered routines. Storage of the generated output files is not mandatory each time the simulator runs, so it has been maintained a file system management, rather than a relational database structure, which is the most common option in this type of Client/Server architecture. The connection between the files and the Web Server is made through a JDBC (*Java Data Base Connectivity*) protocol that allocates queries and different types of operations.

Figure 2 (left), schematizes the architecture of the LNECloss Simulator on the Web. Figure 2 (right), illustrate one of the available interfaces that allows the user to specify the characteristics of a seismic scenario.

Summarizing how the application works: The user (Client), using a Web browser, requests different scenarios simulations through GUI's in JSP and HTML. This request is transmitted to the Server. The Web Server receives the Client request, executes the Simulator routines, manages the files of results and forwards the request to the ArcIMS Connector. This Connector translates the request and forwards it to the ArcIMS Spatial Server, which sends back the response to the Web Server and presents, as an output, a set of maps for the chosen scenario and modeling options made by the user.

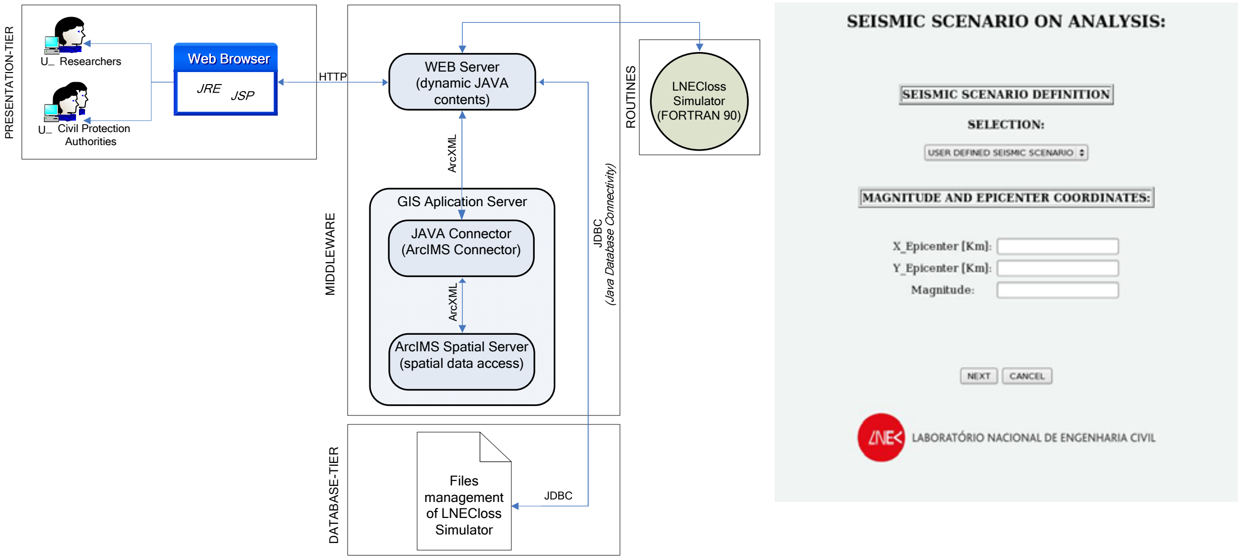

Figure 2. Left: architecture of the LNECloss Simulator on the Web; right: Web interface of LNECloss Simulator (seismic scenario request)

ANALYSIS OF BUILDING DAMAGES AND SOCIAL LOSSES CAUSED BY SEISMIC SCENARIOS

Seismic scenarios in Algarve region

Justification

The 1755 earthquake of 1 of November, known as the Lisbon earthquake, was felt through large parts of Europe, causing heavy damages, mainly due to ground motion shaking and subsequent tsunami, in the Iberian Peninsula and Morocco. In Portugal, the more severe damages occurred in Lisbon, Algarve, that is the Southern Portuguese region, and in the Portuguese Southwest coast. The earthquake magnitude has been estimated, by several authors, as Mw=8.5–8.9. Although the earthquake epicenter was located offshore, its position remains controversial, because, to date, it remains unknown a single tectonic structure able to generate an earthquake with such a magnitude (Sousa *et al.*, 2010).

In the framework of the above mentioned project *Seismic and Tsunami Risk Study for Algarve* (ERSTA), (Sousa *et al.*, 2010) the damages in the residential building stock of Algarve region had already been analyzed, taking into account two ground motion simulated scenarios. The following sub-section presents the adopted ground motion scenarios and damages estimations on Algarve residential building, in order to support the ultimate goal of this section that is to analyze casualties and direct social losses as a consequence of the impact of earthquakes in Algarve region.

Ground-motion and building damage scenarios (Sousa et al., 2010)

The geographic location of Algarve in Portuguese mainland territory is presented in Table 1, together with its global statistics, regarding inhabitants and residential buildings.

Two ground-motion scenarios were implemented to evaluate vulnerability and damages in the residential building stock that currently exists in Algarve region. The first ground-motion scenario corresponds to the seismic motion, at the surface, for an event similar to 1755 earthquake (Figure 3 left), whereas the second is described by an invariable seismic action adopted for the Algarve region in Portuguese National Annex of Eurocode 8 – part 1 (NP EN 1998-1, 2010). The second ground-motion scenario is represented by the yellow series in Figure 3, right, labelled «EC8 - zone 1.2». EC8 – zone1.2 spectrum, and is based on a 475 years return period long distance seismic hazard scenario. Figure 3 also presents the 1755 response spectra simulated in three sites, belonging to the three seismic zones defined in the Portuguese National Annex of EC8 for Algarve region, and compares them with the response spectra adopted in that code, for rock sites. The cities of Sagres, Faro and Vila Real de Santo António are the representative sites of seismic zones 1.1, 1.2 and 1.3 of the Portuguese standard NP EN 1998-1, 2010 (see Figure 3). Sousa *et al.* (2010) used the intermediate seismic action of this National Annex to simulate a constant scenario along Algarve region, aiming at studying the regional variation of the vulnerability of its building stock. The Peak Ground Acceleration (PGA) throughout the Algarve region, for this uniform scenario, has a value of 200 cm/s^2. The same scenario will be used in the next sub-section to analyse the regional variation of human losses.

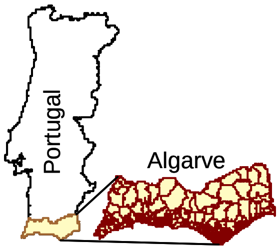	Global Statistics (Censos 2001) (INE, 2002)	
	Parishes	83 (2% of Portuguese parishes)
	No of geographic units adopted: different soil profiles in each parish	222
	Building classes	49
	Residential buildings	160 543 (5,4% of Portuguese buildings)
	Dwellings	276 093 (5,7% of Portuguese dwellings)
	Population	390 310 (4,0% of Portuguese individuals)

Table 1. Geographic location and global exposure statistics of Algarve (adapted from Sousa *et al.*, 2010)

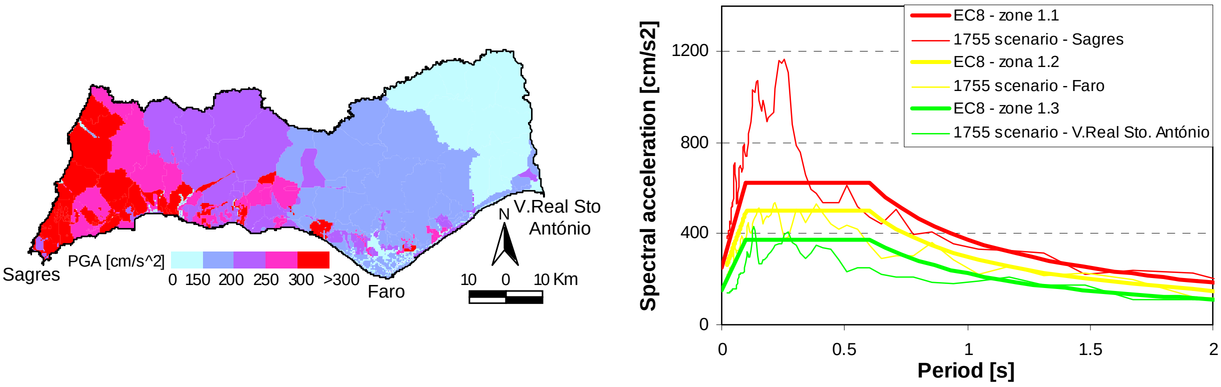

Figure 3. Left: Peak Ground Acceleration (PGA) at surface for 1755 scenario considering the nonlinear behaviour of the stratified geotechnical site conditions; right: response spectra simulated for 1755 earthquake and for a long distance scenario in the 3 seismic zones advocated in Portuguese National Annex of EC8 for Algarve (Sousa *et al.*, 2010)

Figure 4 presents the results of the damage simulations in the residential building stock, existing nowadays in Algarve region, as a consequence of the two seismic scenarios described above. Figure 4 serves a twofold objective. Left figure illustrates the impact of 1755 scenario in absolute terms, whereas the right figure aims at providing information to the analysis of building vulnerability, and so it is presented in percentage terms, in order to control the exposure of elements at risk.

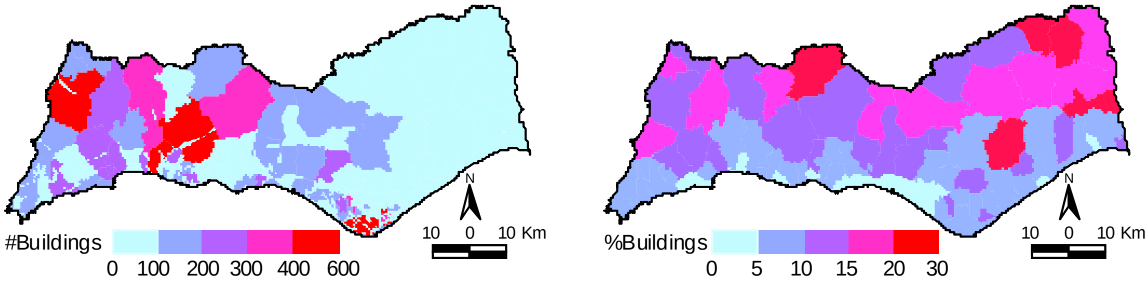

Figure 4. Geographic distribution of collapsed (partial and total) buildings. Left: 1755 seismic scenario; right: 475 years return period invariable scenario (building completely damaged normalized by parish building toll) (Sousa *et al.*, 2010)

Sousa *et al.* (2010) concluded that, as a consequence of a scenario similar to the 1755 event, the Eastern Algarve parishes have a smaller incidence of collapsed buildings than the occidental ones. This result is lined up with the geographic distribution of the ground motion of the 1755 scenario. In Figure 4 (right) the heterogeneity of seismic ground motion was removed, as it was adopted a ground-motion invariable scenario, and the influence of building exposure was also controlled, as the number of collapsed buildings was normalized by each parish' building toll. This figure plays the role of a vulnerability map where it is clear that residential buildings located in Algarve up-country are more vulnerable than the remaining building stock. This result was already expected, because the main urban centers, where the less vulnerable buildings exist, are located at the Southern littoral region of Algarve.

Analysis of human losses

Human losses for Algarve region were estimated, based on the previous strong ground motion and building damage scenarios. Figure 5 and 6 illustrates, respectively, the distribution of the number of dead persons (per geographic unit) and of the number of homeless, for the 1755 and 475 years return period scenarios. Figure 5 and 6 serves a twofold objective, similarly to the previous Figure 4, such as analyzing the impact of 1755 seismic scenario (left) and investigating the population vulnerability to earthquakes (right).

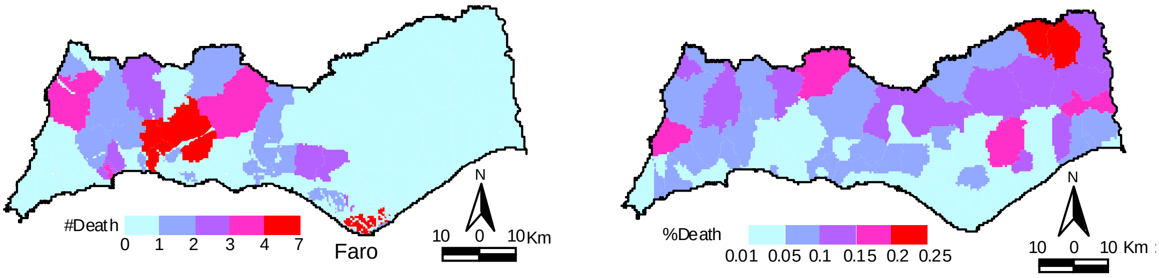

Figure 5. Geographic distribution of deaths. Left: 1755 seismic scenario (dead toll =158); right: 475 years return period strong motion invariable scenario (dead toll =167)

Like in the damage scenarios the severest human losses for the 1755 scenario occur in the Western side of Algarve region, once again lined up with the geographic distribution of the ground motion of this scenario earthquake. Nevertheless, the higher values occur in Faro region, located in the Eastern side of Algarve, due to the population high exposure in this urban area. In fact, Faro is the main city of the analysed district. Figure 5 (right) is a population vulnerability map, as the heterogeneity of seismic ground motion was removed and the number of victims was normalized by each parish' population toll, so the risk is not influenced by the number of inhabitants exposed. Once more it is clear that the inhabitants of Algarve up-country are more vulnerable to seismic events than the remaining population. The number of deaths is slightly higher in the constant scenario than in the 1755 one, because in some regions the seismic intensity (PGA=200 cm/s^2) of the former is higher than the simulated ground-motion of 1755 earthquake; this difference is relevant in the regions where population concentrates, like Faro (see figure 3).

Figures 6 presents the number of displaced households, estimated per geographic unit, assuming that the loss of buildings habitability was exclusively due to structural damages, as the damages in lifelines were not considered in this estimation. Figure 6, left, contemplates not only the geographic distribution of the 1755 ground motion severity, but also homeless concentration in urban centers that is, once again, consentaneous with Algarve population distribution. In the right map, for the constant scenario, the influence of population exposure was controlled, as the number of homeless individuals was normalized by each parish's population toll. Figure 6, right, is in fact a vulnerability map for displaced households, where it is clear that the potential of becoming homeless, due to earthquakes, is smaller in Algarve Southern coast. This vulnerability map for homelessness follows, approximately, the pattern of the building vulnerability map (Figure 4 right).

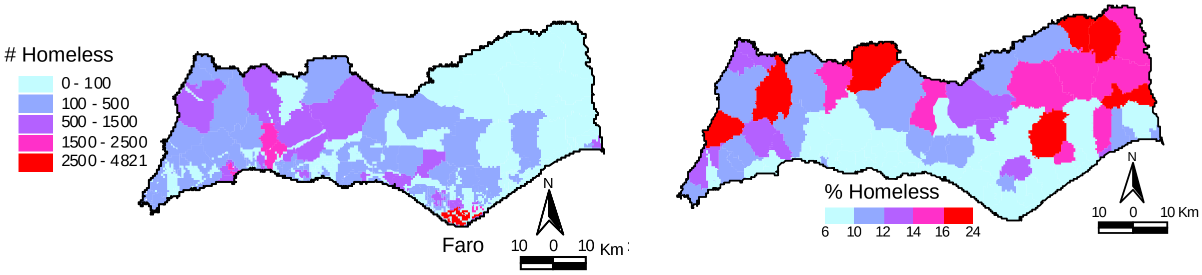

Figure 6. Geographic distribution of displaced households due to structural damage in buildings. Left:, 1755 scenario (homeless toll = 46 137); right: 475 years return period strong motion invariable scenario (homeless toll = 35 619)

Summary of human losses

Table 2 gathers the simulation results for the two seismic scenarios previously analysed. Besides deaths estimates, Table 1 also shows injuries classified by severity level. Furthermore, the presented displaced household's estimations are due not only to building structural damages, but also to the loss of buildings utilities. Only for illustrative purposes and arbitrarily, it was considered that, in the 1755 scenario, 50% of the buildings were affected by losses in power and/or water lifelines, whereas in the 475 return period scenario 10% of the buildings became uninhabitable due to utilities losses. The influence of utilities losses on the number of homeless people is clear in the results. As the death rate assumed in FEMA and NIBS [1999] methodology is often criticized for underestimate scenario results, Table 2 also presents the number of inhabitants in total and partial collapsed buildings, so the reader might perform informal estimations of casualties.

	FEMA and NIBS [1999]	Scenario 1755	Scenario EC8 zone 1.2
Human losses Total = 390 310 individuals in Algarve	No injuries	382 912 (98,10%)	383 327 (98,21%)
	Slight injuries	5 990 (1,53%)	5 630 (1,44%)
	Injuries requiring hospitalization	1 092 (0,28%)	1 019 (0,26%)
	Severe injuries	158 (0,04%)	167 (0,04%)
	Instantaneously killed or mortally injured	158 (0,04%)	167 (0,04%)
	Displaced households due to building structural damages	46 137	35 619
	Displaced households due to building structural damages + loss of facilities	218 144 (50% of the buildings are uninhabitable due to loss of facilities)	71 071 (10% of the buildings are uninhabitable due to loss of facilities)
	No of inhabitants in total and partial collapsed buildings	27 094	23 709

Table 2. Summary of human losses simulations

Faial 1998 earthquake scenario

Observations in 1998 Azores earthquake

The Azores earthquake of 1998 occurred in the early hours of July 9th, a Thursday, at 05h19m (TUC) with the epicentre located around 16 km NNE of the city of Horta on the island of Faial, North of the channel which separates this island from Pico Island (see Figure 7), with a focus located at a depth between 5 and 10 km and reaching a magnitude close to 6.0 (Costa Nunes, Teves Costa and Senos; Oliveira and Malheiros, 1998).

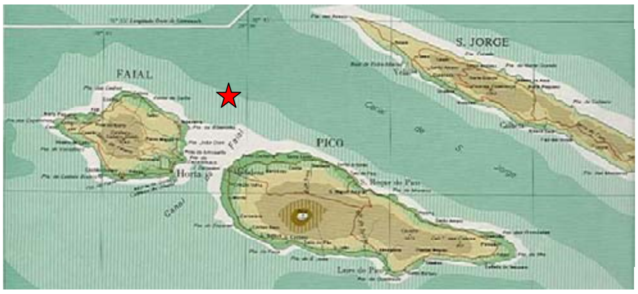

Figure 7. Epicentral location of July 9th 1998 Azores earthquake (Sousa, Rodrigues, Coelho, Carvalho, Salta, Eusébio and Viegas, 2008b)

The main earthquake was felt on the islands of the Central Group of the Azores archipelago, having caused major damage in the built stock, supply networks and infrastructures of the islands of Faial and Pico and some damage on the island of S. Jorge, as well as various collateral effects of a geotechnical nature (landslides and land settlements). In regions closer to the epicentre of the islands of Faial (~ 5 km) and Pico the assigned maximum macroseismic intensities were of VII and VIII, respectively (Costa Nunes *et al*., 1999). The villages most affected by the earthquake were located in rural parishes Northeast of the island of Faial, where many houses of traditional construction of one and two floors were completely or partially collapsed (Lucas, Oliveira and Fragoso, 1999). The building stock in the city of Horta, where about 50% of the population of the island of Faial lived, also suffered damages of significant importance, although with lesser severity, which meant no collapses. On the island of Pico, the extent of the damage was of lower importance, and only the constructions of traditional masonry, located nearest to the epicentre, were severely affected by the seismic movement. On the island of Faial, with near 15,000 inhabitants, the number of casualties caused by the earthquake of July 9th amounted to 8 deaths, to near 110 injured and to near 1,600 homeless families. On the island of Pico, the number of homeless families amounted to 40 (Sousa *et al*, 2008b).

Table 3 (left) shows the number of buildings classified as uninhabitable, as a consequence of the 9th July 1998 Faial earthquake, derived from the number of buildings reported by Ferreira (2008) in D3 (substantial to heavy damage), D4 (very heavy damage) and D5 (destruction) damage grades of the European Macroseimic Scale (EMS98). The same table (right) presents the death toll in 1998 earthquake, distributed by Census track.

EMS98 damage grades	Uninhabitable buildings in Faial	Uninhabitable buildings in Pico
30% of D3	125	39
D4	359	79
D5	90	7

Faial Census track (parish)	Deaths [#] Total = 8
Ribeirinha	5
Pedro Miguel	2
Salão	1

Table 3. Left: Uninhabitable buildings in Faial and Pico, following Ferreira (2008) survey. Right: number of deaths in 1998 Faial earthquake (Sousa and Afonso, 2008)

Simulation of the effects of Faial 1998 earthquake

The simulation of the effects of 9th July 1998 Faial earthquake was based on a 6.2M_W scenario, located at the epicentre foreseen by Madeira, Silveira and Serralheiro (1998) (38.64ºN, 28.59ºW). Faial 1998 earthquake ground motion was simulated based on empirical attenuation law published by Bommer, Elnashai, Chlimintzas and Lee (1998). Results of this ground-motion scenario are presented in Table 4.

Island	Total damage [#]	Deaths [#] Coburn and Spence (2002)	Deaths [#] FEMA and NIBS (1999)
Faial	314	37	8
Pico	61	1	1

Table 4. Total damaged buildings and death toll simulated in Faial and Pico islands (Sousa *et al,* 2008a)

Figure 8, left, illustrates a map of isoseismals observed in 1998 earthquake in Faial Island and Figure 8, right, the geographic distribution of collapsed and partial collapsed buildings («Total Damage») for the simulated ground motion.

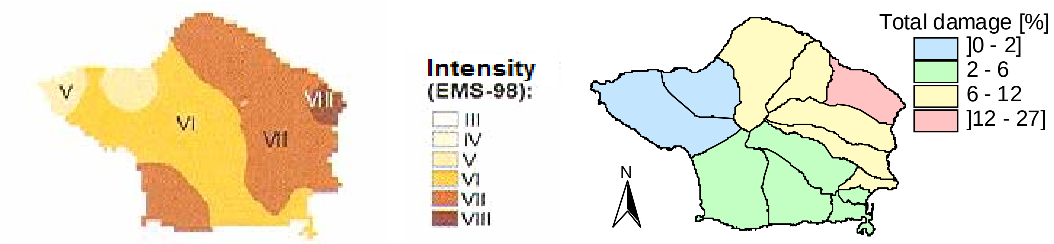

Figure 8. Left: Isoseismals of 1998 earthquake in Faial island (Ferreira, 2008); right: geographic distribution of buildings in «Total Damage» state (Sousa *et al,* 2008a)

Simulated losses shows a good agreement with the observations, except for Coburn and Spence (2002) casualty model that overestimates the death toll observed in 1998 earthquake.

FINAL CONSIDERATIONS

LNECloss simulator is a spatial decision support system designed to provide geo-referenced information for different end users, namely decision makers and researchers. Once an earthquake occurs, LNECloss may quickly simulate a seismic scenario, similar to the earthquake just occurred, with impact in Portuguese parishes, offering critical information for emergency management and for crisis response and recovery. Moreover, in a research framework, the simulator may be used as an automatic tool that assesses damage and losses and, consequently, help to delineate seismic risk mitigation strategies based on alternative seismic scenarios.

The update of LNECloss simulator to a GIS Web service may benefit end-users, with no GIS proficiency, to foster the development of measures of prevention and may help to draw more efficient emergency plans for a quicker response and coordination.

Improvements should be expected in the future, namely the upgrading of the GIS Web service to a more recent type of technology, like ArcGIS Server.

LNECloss is able to evaluate seismic action at bedrock and at surface level, earthquake damage to buildings and is able to estimate human and economic losses as a consequence of any plausible scenario affecting Portugal. However, the Simulator was mainly calibrated, till now, with the information collected in historical events (1755, 1909 earthquakes), because damaging events are infrequent in Portugal, except for Azores Archipelago.

Two distinct examples of the analysis of building damages and social losses, caused by seismic scenarios, were presented. These examples aims at illustrating the versatility of the Simulator, that is able to support different kind of applications.

In Algarve, we may conclude that seismic losses will have a great impact in urban regions, although the concerns in the vulnerability of buildings and population should be targeted to up-country less urbanized parishes.

On the other hand, the Azores Archipelago is the only Portuguese region that was recently struck by damaging instrumental earthquakes, like the 1998 event, offering a unique opportunity to collect valuable information that can be used in seismic risk studies. Earliest damage survey of the 1998 earthquake needs to be re-analysed and processed, enabling the comparison of damages estimates with damages observations, in order to calibrate simulation models.

Nevertheless, effective risk mitigation strategies should not be restricted to the evaluation of a single scenario event based on probabilistic or deterministic analyses, because, in practice, any future event will produce significantly different effects depending on the assumed scenario. In conclusion, we propose that, beyond seismic scenarios, seismic risk mitigation strategies should also take into consideration a probabilistic seismic risk assessment.

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