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The e-Risk model applied to damage simulation

Oliveira C.S.(1), Mota de Sá, F.(2), Ferreira, M.A.(1), Nunes, J.C. (3)

(1) Instituto Superior Técnico, Lisbon, csoliv@civil.ist.utl.pt; monicaf@civil.ist.utl.pt
(2) Fuzzy Engenharia de Sistemas e Decisão, Lda., Lisbon, mota.sa@netcabo.pt
(3) Universidade dos Açores., Ponta Delgada, jcnunes@notes.uac.pt

Abstract

In recent years several studies essentially developed under two Projects PPERCAS and USuET led to the assemblage of an earthquake simulator e-Risk capable to compute earthquake losses for a stock of buildings and a group of lifelines, given a sourceand a magnitude. e-Risk is composed by several modules from wave attenuation, soil influence, structural characterization and their inventory, vulnerability functions, to damage assessment of a given stock of buildings, to population affected. This Simulator used a large amount of data compiled in a book published on the event of the 10th Aniversary of the 1998 Azores Earthquake to improve its algorithms. This paper presents some of the most interesting features of e-Risk and compares results with observed damage data for the 1998 earthquake in the city of Horta, Faial. It includes new developments in (i) the detailed geological description of Horta, (ii) the finite-fault model for strong motion simulation, (iii) the ambient vibrations analysis of the surface geology and H/V interpretation, (iv) the detailed inventory characterizing the building stock, including the in-situ measurement of natural frequencies, (v) to the standard building damage classification of 6 classes (D0 to D5), a class D5+ was added to represent to tal collapse of structures, (vi) the real building damages inflicted during the July 9, 1998 event. The e-Risk developed under GIS technology, produces results, using the European Macroseismic Scale (EMS-98) methodology showing a few discrepancies with real data which were essential for calibrating the various parts of the model.

Key-words: earthquake simulator, microzonation, vulnerability of low-rise masonry buildings, damage, Azores

1. Introduction

Horta the capital of Faial Island in the Azores Archipelago is a geological risk area with seismic and volcanic activity along the history as well as suffering from landslides and floods. Recently, several studies were developed to compile a book on the event of the 10th Anniversary of the1998 Azores Earthquake contributing to new studies and research. The present paper intents to join different studies carried out with new contributions as (i) the geological description (Nunes, 2008), (ii) the finite-fault model for strong motion simulation (Zonno *et al*., 2008), (iii) the ambient vibrations anal-

ysis of the surface geology and H/V interpretation (Teves-Costa *et al*., 2008), (iv) the detailed iventory characterizing the building stock, including the in-situ measurement of natural frequencies, (v) to the standard building damage classification of 6 classes (D0 to D5), a class D5+ was added to represent total collapse of structures, (vi) the real building damages inflicted during the July 9, 1998 event Finally, an earthquake simulator (e-Risk) was developed for generate seismic risk scenarios using GIS technology (Oliveira *et al*., 2008, Mota de Sá *et al*., 2008). The standard building damage classification includes 6 classes (D0 to D5); in this work a class D5+ is introduced, which means the total collapse of structures, in order to obtain more realistic damage pattern for estimating casualties.
The e-Risk results in terms of damage were correlated with the observed damage data, classified according to the European Macroseismic Scale (EMS-98) (Ferreira, 2008). This correlation, made building by building, showed few discrepancies which were essential for callibrating the model.

1.1 The Collecting of Data - Horta case study

The necessary information to explain and recreate new damage scenarios was acquired from diferent projects developed during the last decade. A brief description for that aim is presented in this section.

1.1.2. The Azores seismicity

Azores Archipelago (Fig. 1a) located at the triple junction of the Eurasian, North American and Nubian plates is the most important seismogenic area of Portugal with high seismicity. A total of 28 seismogenic areas (Fig. 1b) define the Azores Region with different magnitude/frequency relationships, which, in terms of seismic hazard studies (e.g. building stock codes), should be taken in consideration. In general terms, four main seismotectonic systems can be defined: i) the islands of São Miguel, Terceira and Faial (with higher seismicity, frequent felt earthquakes that reach MMI≥V); ii) the islands of Pico and São Jorge; iii) the islands of Graciosa and Santa Maria and iv) the islands of Flores and Corvo, on the North American plate with reduced seismicity.

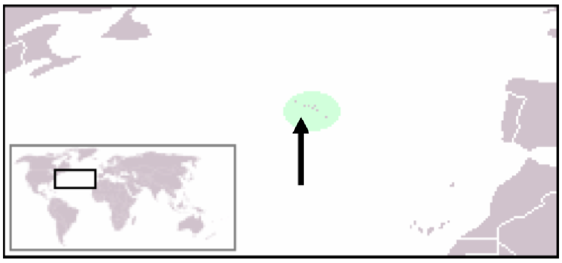
Figure 1a: Location of Azores.

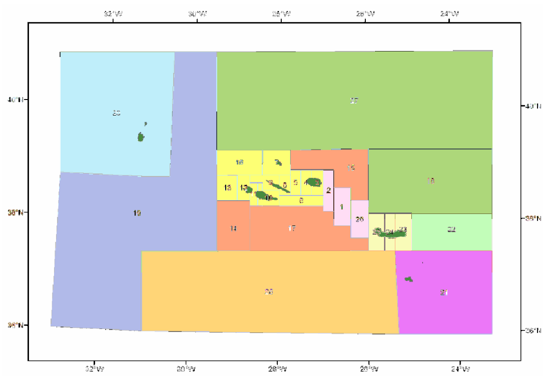
Figure 1b: Seismogenic areas – Azores Archipelago.

Table 1: Brief description of principal events that affected Faial Island (in Nunes *et al*.,2001)

Date & Time	Local/Island	Epicenter/depth	Magnitude	Maximum intensity	Deaths
1926-08-31 10:42	Horta, Faial	38,5ºN/28,6ºW 1,6-4,8 km	Mb=5,3-5,9	X	9
1973-11-23 13:36	Bandeiras, Pico	38,5ºN/28,4ºW 16 km	Mb=5,0	VII-VIII	
1998-07-09 05:19	Ribeirinha, Faial	38,7ºN/28,5ºW 1,2 km	Mb=6.2	VIII-IX	8

1.1.3. Geological Description and Soil Characterization

Based on the geotechnical classification proposed by Forjaz *et al*. (2001) for the Azorean geological formations (Table 2), the results of some geotechnical tests carried out through the years by

LREC – Regional Laboratory of Civil Engineering, were collected and analyzed with the purpose to characterize the more representative geologic formations of the Azores islands. This overall description was detailed in the area of the city of Horta (Nunes *et al.*, 2008) presenting the surface geological units (Figure 2a) and the interpretation of soil layers in terms of the EC-8 classification (2004), Figure 2 b.

a) b)

Figure 2: Geological map of Horta city area (Nunes *et al.*, 2008) and classification categories according to EC-8 (2004).

Table 2: Geotechnical classification of Azores Islands geological formations.

Group	Subgroup	Description
Hard (I)	I a	Trachitic s.l. lava flows (including coulées and domes)
	I b	Basaltic s.l. lava flows
	I c	Welded ignimbrites
	I d	Surtseyan tuffs (hyaloclastites)
Intermediate (II)	II a	Non-welded ignimbrite and *lahars*
	II b	Slope, alluvium and beach sand/gravel deposits
Soft (III)	III a	Pumice and other trachyte s.l. pyroclastic deposits
	III b	Basaltic s.l. pyroclasts (scoria)

1.1.4. Predominant frequencies of soil layers

One part of the study involved the characterization of the shallower layers was developed (Teves-Costa *et* al., 2008) using ambient vibrations analysis. Nakamura's methodology developed for the analysis of ambient vibration has been applied in the town of Horta (see Figure 7 for location) for the dynamic characterization of the surface layers in sedimentary regions. However, due to the particular geologic cover of this town, composed by pyroclastic deposits with irregular thickness (between 0 and 10 m), the interpretation of the H/V curve is very hard. An association of frequency peak of the H/V curve, with the thickness, of the surface layer was used. SHAKE program had calculated the transfer function of soil columns with several surface layer thicknesses. We tried to fit the H/V curve for points with the same surface layer thickness with the transfer function, adjusting the S wave velocities (there are no measures of this parameter). Figure 3 shows soil frequencies associated to each building in order to understand the soilstructure interaction.

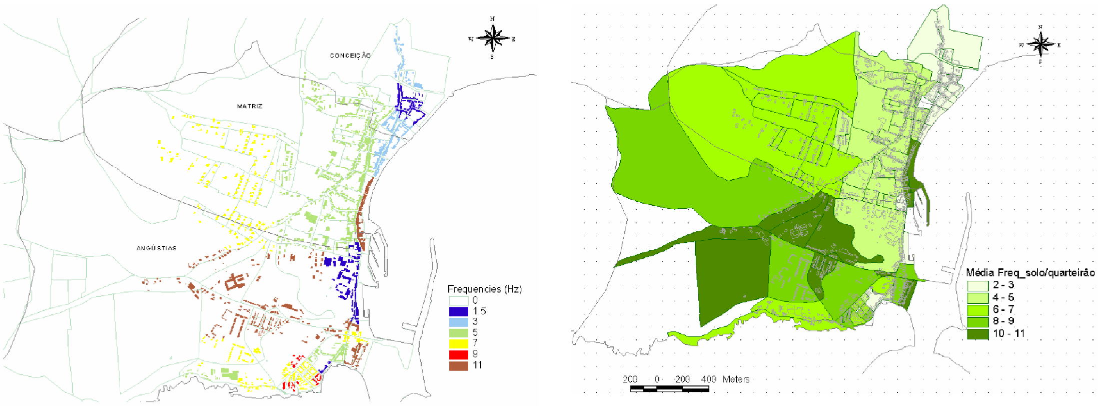

Figure 3: Left: peak frequency of the H/V curves (adapted from Teves-Costa *et al.*, 2008). Right: average of soil frequencies (Hz) by city block (Horta urban centre).

1.1.5. Strong motion simulation

A stochastic strong ground motion procedure was applied (Zonno *et al*., 2008) on Faial and Pico islands using published fault solution, the moment magnitude and the rupture mechanism of the 1998 earthquake. Recordings at near-field Horta station were used to constraint model parameters such as response acceleration spectra and the high frequency spectral decay parameter, k (Anderson et al., 1984). Low amplitude Peak Ground Acceleration (PGA) values at Terceira and S. Miguel islands were used as qualitative constraints for the far-field simulations. Maps of average PGA at bedrock were derived and relationships between PGA and MMI (Wald *et al*., 1999) were used to retrieve intensity.

In this study we considered two scenarios of the July, 9 1998 Faial earthquake: epicentre EPI 1 (Latitude 38.634ºN, Longitude 28.523ºW) as defined by Matias *et al*., (2007) and EPI 2 (Latitude 38.640ºN, Longitude 28.590ºW), about 2 km closer to the Horta site, and was derived by Oliveira from damage analysis and adapted from Madeira, 1998. Due to the presence of real data on d mage buildings was possible to construct new formulations and models to better explain the reality. Per example, as shown in Fig. 4, the elliptic propagation of the seismic wave, where isolines of PGA are ellipses centred in the epicenter and with the major axis coincident with the projection of the fault in the surface, raised a very good explanation to the observed values (Mota de Sá *et al*., 2008).

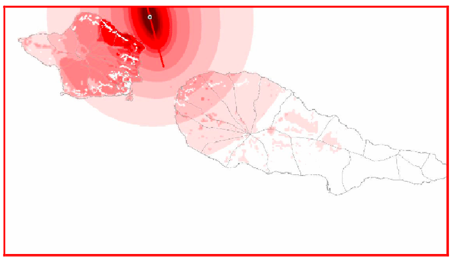

Figure 4: Elliptic propagation of seismic waves with EPI 1 model.

1.1.6. Building stock characterization

In the aftermath of Faial event several surveys were carried out in order to collect data related to damage inflicted:

i) PPERCAS project (FCT, Praxis XXI), developed in the period 1997-2001, contributed to a building by building field work inventory where it was possible to locate the buildings in Horta centre. (Figure 5 and 6) and associate a vulnerability index to each building (according to the knowledge of 7 factors: soil, slope, building height, state of preservation, type of construction, position of agregate buildings – middle, corner, header -, discontinuity with adjacent buildings, and damages inflicted by Faial earthquake). Figure 5 shows the damages obtained in each single building.

ii) A *in-situ* campaign for obtaining the predominant (first) frequencies of buildings in their city blocks was performed for a number of different buildings and correlation with number of stories was established (empirical equation). Figure 6 presents the average frequency of each "city block", based on the average number of stories per city block and on the above mentioned empirical equation.

Figure 5: Damages occurred with Faial earthquake.

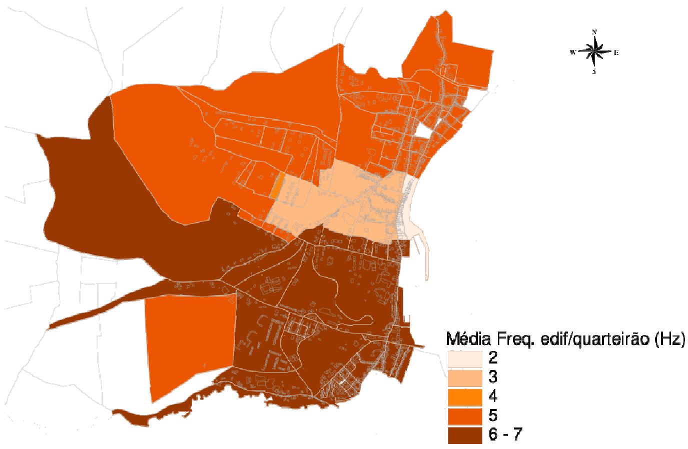

Figure 6: Average building frequency per city block.

iii) Many data bases were developed by various partners during the process of reconstruction, so it was necessary create an "algorithm" for merging all information into a single integrated data base (Neves *et al*., 2008). This is organized building by building and contains only those buildings afected by the earthquake. Data includes a general characterization of the building (geometry, predominant materials, structural type, etc.), damage inflicted, and type of reconstruction and costs of intervention. Table 3 summarizes the most common buildings structural system in the Faial Island. A total of 2151 buildings in Faial had been georeferenced using GIS software. This allowed geospatial analyses of the data and was used to understand, for instance, the distribution of buildings damage grade within a given area.

Table 3 - Short description of common structural system in Faial island

Construction class	Short description
CT	"construção tradicional" - known as traditional construction: the structure is mainly stone masonry with wooden floors and wooden roof
CTA	"construção tradicional alterada" - very similar to the traditional construction (structure in stone masonry and wooden roof), but part of the floors (often bathroom and kitchen) are concrete slabs
CM1	"construção mista 1" - structure in masonry stone, concrete floors and wooden roof
CM2	"construção mista 2" - the structure is masonry stone but there are concrete columns and beams, wooden floors, wooden roof and concrete enlargements
CM3	"construção mista 3" - concrete columns, beams and floors, and either wooden or concrete roof
CC	"construção corrente" - earthquake-resistant structures, almost all elements of the house are concrete, except for the roof that might be in wood

Various vulnerability models were developed either based on EMS-98 (Giovinazzi *et al.*, 2004) and on estimated capacity curves (Costa et al. 2008) for the structures under analysis and comparison with observed data in different locations of Faial Island were made.

1.1.7. e-Risk simulator

The Earthquake Simulator (*e-Risk*) is a tool able to determine the damage inflicted by an earthquake characterised by a certain magnitude and epicentral location and rupture mechanism related to a given fault, based on a GIS technology (Mota de Sá *et al.*, 2008; Oliveira *et. al.*, 2008). This permits the end-user to carry out a complete seismic risk assessment and produce seismic risk scenarios and seismic risk maps at three geographical scales: "freguesia (city council)", "sub-secção estatística (city block)" and individual building (Fig. 7).

Figure 7: left – Real damage observed after 1998 earthquake (Ferreira, 2008) from "integrated data base". Right – *e-Risk*: Calculated intensities in Faial Island for the 1998 earthquake. Isoline in blue represents PGA (cm/s^2); dots are buildings damaged; intensities were computed for urban areas with a radius of influence of 3 km. (see location of Horta).

2. Results and Discussion

Based on observed damages in 1327 buildings in Horta City (data from PPERCAS project), *e-Risk* compared the damages obtained after the 1998 earthquake (PPERCAS project) with new damages obtained by the simulator model (Fig. 8).

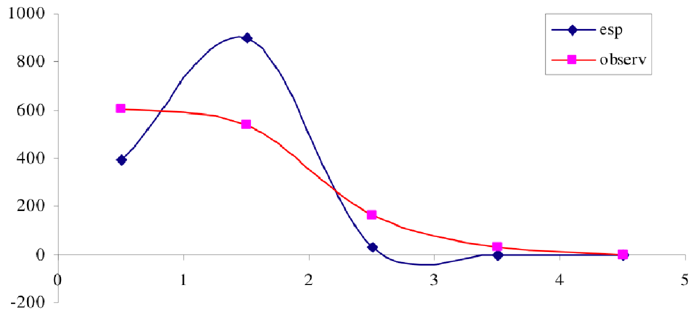

Figure 8: Comparison between real observed damage and expected damage (e-Risk model).

Analyzing the results building by building we see that the expected damage (D1) are higher than the observed in 1998, but in a global sense the mean damage grade error is only 0.01.

Results express that different typologies showed larger different aggravation vulnerabilities than expected. For these observations, the expected vulnerability (Vu) was calculated as a function of observed Intensities (I) and mean damage grades (mdg) by:

$Vu=2,19334-0,18205\times I - 0,337703\times Arctanh(0,962698 - 0,396825\times mdg)$

And the aggravation factor could be found by:

$Vu=2,19334-0,18205\times I - 0,337703\times Arctanh(0,962698 - 0,396825\times mdg)$

And the aggravation factor could be found by:

D*Vu* = *Vu.Observed* −*Vu.Expected*

Then, One-way ANOVA was conducted, and the Mean(ΔVu) was tested.

Ho: Mean (ΔVu) equal to RC3, RC2, W,…, M1

Test results are shown below:

Source	DF	SS	MS	F	P
Factor	6	12.6430	2.1072	36.43	0.000
Error	1321	76.4087	0.0578		
Total	1327	89.0517			

S = 0.2405 R-Sq = 14.20% R-Sq(adj) = 13.81%

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                                 Individual 95% CIs For Mean Based on Pooled StDev
Level      N     Mean   StDev     --+---------+---------+---------+-------
RC3       38   0.1899  0.2146                                  (----*----)
RC2,W    160   0.0787  0.1925                             (-*--)
RC1       44  -0.0540  0.2252                 (---*----)
M5       154  -0.1260  0.2266             (--*-)
M3       534  -0.0355  0.2461                        (-*)
M2       269  -0.0766  0.2589                    (-*-)
M1       129  -0.2779  0.2581     (-*--)
                                  --+---------+---------+---------+-------
                                  -0.30     -0.15      0.00      0.15
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So, because the test statistics P=0.000 < α=0.05, the Null Hypothesis (Ho) was rejected, and we can then conclude that: different typologies have different vulnerability degradation.

We can also observe that "old constructions" {M1, M2, M3, M5, RC1} showed better performance than expected (aggravation factor, Mean (ΔVu) < 0, so: lower vulnerability than expected). In opposition, more recent typologies showed a worst behaviour than expected (Mean (ΔVu) > 0, so: higher vulnerability than expected, i.e. greater damages than expected).

2.1. Future developments

e-Risk will evolve in the near future in several different areas. First, a friendly-user graphic interface where the researcher can change fault location at will, decision on the area under analysis and on the scale of work can be specified. Also, another module to compute impact of earthquake taking into consideration the interaction and interdependence of facilities will be added.

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