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URBAN SYSTEM UNDER EARTHQUAKE THREAT APPLICATION TO THE AZORES

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SUMMARY

Assessing and managing earthquake risks are topics being developed in recent years. The present project (USuET) follows a previous one developed in the period 1997-2001, which contributed to the seismic hazard and risk assessment in the Central Group of the Azores Archipelago. The present project aims at the development of a general methodology for creating earthquake-risk scenarios that takes into consideration the distinctive features of Azores. Particular attention will be given to the response of the urban centres behaving as an entire system, considering the economic impact and population reaction (Hollistic view).

In order to achieve this goal some detailed methodologies will be developed to analyse the vulnerability of existing housing in large towns of Terceira, Faial and Pico, applying the EMS-98 macroseismic scale concepts and mechanical techniques to model seismic response of buildings constructions. The influence of the soil layers (geological and geomorphologic effects), slip in mapped faults and evaluation of the possible landslides and liquefaction will be taken into account.

An automatic seismic scenario loss estimate methodology integrated on a Geographic Information System (GIS), which comprises modules evaluating bedrock seismic input, local soil effects, vulnerability and fragility analysis and human losses analysis will be applied to Azores Archipelago. This permits the end-user to carry out a complete seismic risk assessment and to produce seismic risk scenarios and seismic risk maps at three geographical scales: "freguesia (city council)", "subsecção estatística (city block)" and individual building. The application of system analysis to urban centres in Azores (USuET project) will be an important tool to help emergency planning, online impact evaluation, and for urban and land-user planners.

1. INTRODUCTION

The Azores Archipelago is a high seismicity region because is located in the triple junction region between the N. American, Eurasian and African plates.

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In 1980 The Angra do Heroismo town (Terceira Island) was on New Years day struck by an earthquake (M_w= 7.2). Many of the buildings in the centre of the town were destroyed. The Pico-Faial (9 July 1998) earthquake M_w= 6.2 was one of the largest instrumental earthquakes occurred NE of Faial Island, on the last years and shook Faial, Pico, São Jorge, Terceira and Graciosa.

A project (PPERCAS) funded by Fundação para a Ciência e a Tecnologia in the period 1997-2001 contributed to the determination of the hazard and risk in the Central Group of the Azores Archipelago. It essentially consisted in launching a series of studies necessary to develop knowledge in those areas. For five cities in the Azores the inventory, building by building with information of height, structural type, etc. was made during PPERCAS. This data will be combined with Census data and apply vulnerability studies at three different scales (city council; city block; individual building) to evaluate the errors involved.

The results presented in this paper are for one city in Pico (Lajes do Pico) and two cities of Terceira Island (Praia da Vitória and São Sebastião). Future work will include other more important cities such as Angra do Heroismo in Terceira and Horta in Faial Islands. The methodology used on this work consists of the following phases:
i) analysis of the surveys realised in 2000 and reclassification of the building stock (using the concepts of European Macroseismic Scale – 98 (EMS-98));
ii) data treatment and identification of the most important parameters characterising the seismic behaviour of buildings; and
iii) creation of a simulation model to analyse the damage inflicted to the building stock and to the population of Pico and Terceira.

2. BUILDING STOCK ANALYSIS

In this first phase, 2522 buildings were reviewed and analysed from the data collected in PPERCAS project. In 1999 and 2000, the building stock of São Sebastião and Praia da Vitória villages was characterized and studied in detail. In 2005 the same work was made to Lajes do Pico and Almagreira villages, aimed at the assessment of vulnerability maps of those areas. The building survey was carried out, to identify the following main parameters: number of storeys, constructive typology, state of preservation, building use, location inside the block, etc.

The reference for the classification of the buildings was EMS-98 which consider some typologies for masonry (M1 to M7), reinforced concrete (RC1 to RC6), steel (S) and timber buildings (W). In Azores the most common are M1, M2, M3, M5, RC1, RC2, RC3 and W. The buildings reclassification was a very difficult task because we only made use of the videos and the surveys that do not make reference to the epoch of construction or group of construction types. Figure 1 presents the general layout of the Lajes do Pico village with buildings analysed by typologies.

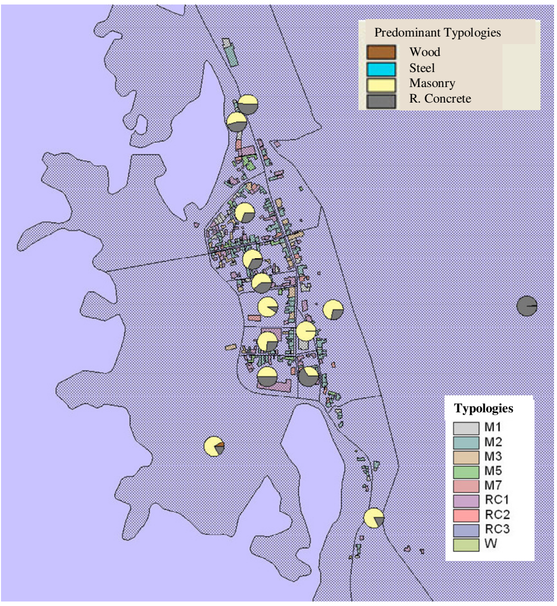

Figure 1: Lajes do Pico typologies

2.1 Pico Island

The maximum intensity verified on the Pico Island was VIII during the 1926 earthquake crisis. Relatively to Lajes do Pico village, a maximum intensity of VI/VII was detected on the 9 of July 1998 earthquake ($M_w = 6.2$). Almagreira was one of the zones where occurred severe damages through the 1998 earthquake. The houses were constituted basically by stone and 1-2 storeys, that had several damage and some parts collapsed. Fortunately there were no victims.

2.2 Terceira Island

The maximum intensity was VIII and a local tsunami was observed during the 1980 crisis. The earthquake causes 63 dead, 400 injured and leaved about 20 000 homeless. The intensity observed in São Sebastião was on the order of VIII, while in Praia da Vitória was IV/V.

2.3 Population

To map and know the population location we used the Censos 2001 data (Figure 2). In the scope of the emergency planning, it matters to estimate the number of population affected by an earthquake. This study had been in consideration different population scenarios, for different phases of the day and the year to obtain a more realistic model.

Figure 2: Lajes do Pico typologies

3. AZORES SOIL CLASSIFICATION

The surface geological of Terceira, Pico and Faial were classified into three categories or groups [Forjaz et al., 2001]: "hard", "intermediate" and "soft" formations. This classification can be compared with the new regulations for definition of the seismic action, Eurocode 8 [EC8, 2002] as shown in Table 1.

Table 1: Geotechnical soil classification of Azores Archipelago and comparison with Eurocode 8

Group	Subgroup	Average shear wave velocity (m/s)	Subsoil class (EC-8)
Hard	Ia	> 400	B
	Ib		
	Ic		
	Id		
Intermediate	IIa	200-400	C
	IIb		
Soft	IIIa	< 200	D
	IIIb		

In case that local studies were made to obtain the predominant frequencies from *in situ* noise measurements [Pena et al., 2001] we have used the values reported.

3.1 The Attenuation Relationships

Earthquake shaking is usually very strong at distances very close to the fault and decreases or attenuates with increasing distance to the fault. The attenuation depends on the magnitude of the earthquake, and geology of the regions. Soft soils can greatly increase or amplify the ground motion, so shaking can still very strong at a large distance if a building is located on a poor soil [Chen, 2003]. The attenuation relation used in the present study can be described by the expressions:

$$\ln(a_0) = -5.0 + 0.9M - \ln\left(\sqrt{Df^2 + M^2}\right) - 0.5 \cdot Df \cdot \frac{1}{(M+7)^2}(*980) \quad , \mathrm{M} \leq 4.5 \tag{1}$$

$$\ln(a_0) = -4.5 + 0.9M - \ln\left(\sqrt{Df^2 + M^2}\right) - 0.5 \cdot Df \cdot \frac{1}{(M+7)^2}(*980) \quad , \mathrm{M} > 4.5 \tag{2}$$

In the above equations (1 and 2), a_0 is the peak ground acceleration (PGA), M is magnitude and D_f is the distance from the site to the source of the earthquake (km). These equations were calibrated for Pico Island for the 1973 and 1998 earthquake but for other islands a different expression should be used. In further studies we will take these differences into account, making use of intensity and strong motion attenuations [Paula, 2001, Oliveira *et al.*, 2004].

From the knowledge of superficial geology, the predominant frequencies of these layers and the predominant frequency of the seismic action (function of the epicentral distance and magnitude) we used the concept of "single degree of freedom", to estimate the maximum acceleration on the surface, a_{soil}:

$$a_{soil} = a_0 \beta \beta_0 \tag{3}$$

$$\beta = 1 / \sqrt{\left(1 - \left(\frac{f_{earthq}}{f_{soil}}\right)^2\right)^2 + \left(2 \cdot \xi \cdot \frac{f_{earthq}}{f_{soil}}\right)^2} \tag{4}$$

$$\beta_0 = \sqrt{1 + \left(2.\xi.\frac{f_{earthq}}{f_{soil}}\right)^2} \tag{5}$$

In equations (3 to 5), β and β_0 are amplifications, f_{earthq} and f_{soil} (Hz) are earthquake and soil frequencies and ξ is the damping ratio equal to 0.20.

As the peaks of the attenuation function are very sensitive and because of the width of the seismic spectra in bedrock, we had calculated the values of the amplifications for three points, took the value of the formula and more two points with a 20% interval and the maximum value is chosen.

The earthquake frequencies could be obtained using equation (6) [Kramer, 1996], which was computed from several hypothesis.

$$f_{earthq} = \frac{1}{\left[(0.007 \times e^{(0.613M)}) D_f^{\,0.12}\right]} \tag{6}$$

Although some amplifications were recorded by the accelerometers stations, those amplifications could be too much serious for the calculation of buildings vulnerability. In this way we should have some attention relatively to the use of this formulation.

The intensity was defined by the equation (7), which is consistent with some author's proposals, adapted from [Richter, 1958, Paula, 2001] and reproduces some of the values obtained in Azores earthquakes.

$$I = 0.4254\log(a_{soil})^3 - 1.4932\log(a_{soil})^2 + 4.1869\log(a_{soil}) + 0.1495 \qquad (7)$$

In order to obtain the influence of the predominant frequencies of the buildings, given in function of the typology and number of floors, we considered equation (8) to correct this effect.

$$\beta_1 = 1/\sqrt{\left(1-\left(\frac{f_{earthq}}{f_{build}}\right)^2\right)^2 + \left(2\cdot\xi_{build}\cdot\frac{f_{earthq}}{f_{build}}\right)^2} \qquad (8)$$

where, β_I is the acceleration amplification and ξ_{build} the building damping equal to 0.10. The buildings frequencies (f_{build}) used in this study are as follows (Table 2):

Table 2: Building frequencies

Number of floors	Frequencies (Hz)
1	7
2	5
3	3

Consequently, the building acceleration is obtained using equation (9):
$a_{build} = a_{soil}\beta_1$ (In future studies we will use the response spectra concept to take care of this influence). (9)

The new intensity defined in equation (10) will be used to calculate the mean damage grade, μ:

$$I = 0.4254\log\left(a_{build}\right)^3 - 1.4932\log\left(a_{build}\right)^2 + 4.1869\log\left(a_{build}\right) + 0.1495 \qquad (10)$$

The bed-rock intensity, I_{BR}, is calculated using equation (11):

$$I_{BR} = 10.3 + 0.95M - 2.6\ln(Df + 7) - 0.7Df^{-1/2} \qquad (11)$$

4. VULNERABILITY MODELLING

In the present work we emphasise the analysis of vulnerability based on EMS-98 interpretation, using the concepts described in the EMS-98 scale [Grunthal, 1998], and implemented by Giovinazzi and Lagomarsino [Giovinazzi, 2002]. The seismic behaviour of building in terms of damage could be classified in six vulnerability classes as shown in Figure 3.

Probability Damage Matrices and Mean Damage Grade are obtained as proposed by Giovinazzi and Lagomarsino (2002) through the vulnerability index V_I. In the proposal equation (12) the mean damage grade μ_D is function of the Macroseismic intensity I, only depending from the parameter V_I:

$$\mu_D = 2.5\left[1 + \tanh\left(\frac{I + 6.25V_I - 13.1}{2.3}\right)\right] \qquad (12)$$

The passage from μ_D to damage grades characterized by six limit states ("no damage"; "slight damage"; "moderate damage" ; "heavy damage" ; "very heavy damage" ; and "collapse"), we use the beta distribution as recommended by ATC 13 (1985).

Application of penalizing functions considering the number of floors, state of conservation or other factors will be the subject of further studies. All the necessary data for this analysis is available through the GIS database. Mean damage ratio by administrative blocks of buildings, minimum and maximum values of damage, were obtained. Numbers of collapsed and severe damaged buildings were also computed. A few of these values are presented for typical earthquake scenarios.

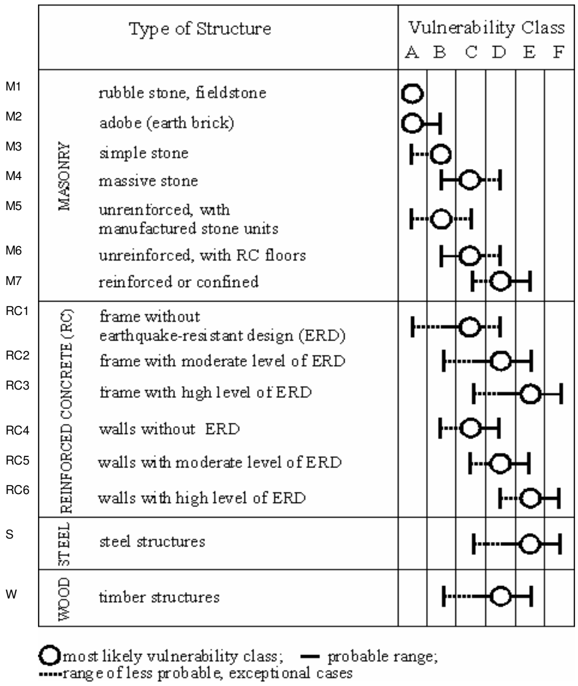

Figure 3: Attribution of vulnerability classes to different building typologies

5. AN APPLICATION OF THE MODEL TO TERCEIRA ISLAND

The parameters that have been explained above was connected to a GIS by an application carried out to Pico and Terceira Islands (see Figure 4).

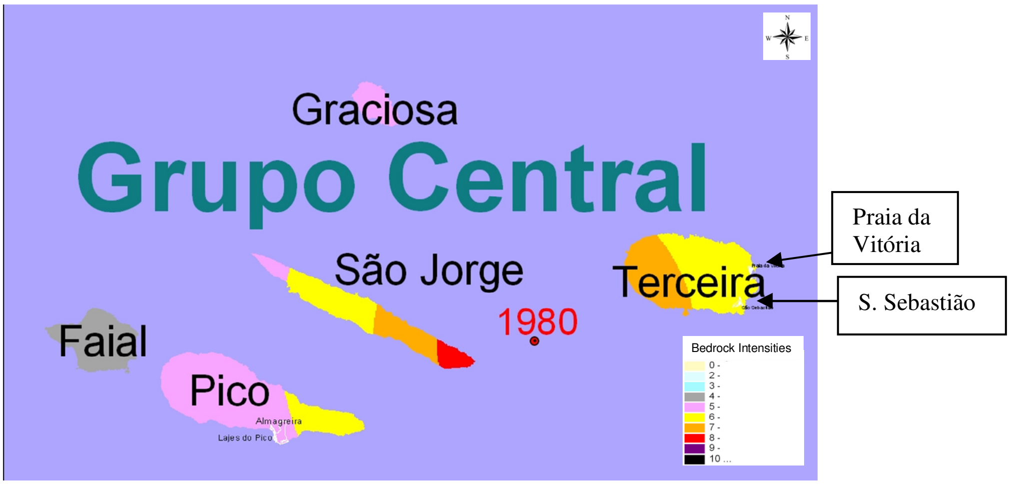

Figure 4: Azores Central Group

The deterministic input chosen for the simulation corresponds to the earthquake that hit the region in 1980, ranging VII-VIII on the EMS-98 scale (Bedrock intensity).

The results of the analysis (see Figures 5 to 7) showed VIII intensity in São Sebastião village which generates some severe damages on buildings, but not the collapse.

About 1 to 6 buildings by block could demonstrate severe damages, as observed in Figure 5. In 1980 São Sebastião suffers some important damages on building stock due to the low soil frequencies (2 to 3 Hz). The soil amplifies the low frequencies, especially to the 1980 earthquake (focal distance equal to 120 km) where the seismic frequency was coincident with the São Sebastião soil, causing some damages.

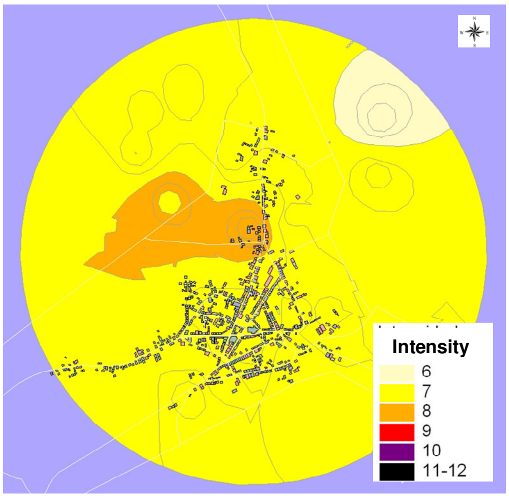

Figure 5: Maximum Intensity in São Sebastião (Terceira Island)

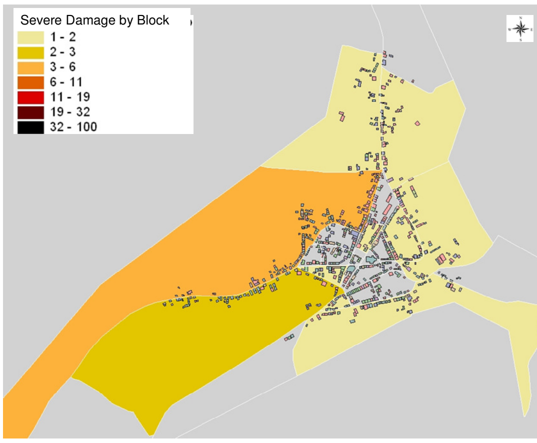

Figure 6: Severe damage by block in São Sebastião (Terceira Island)

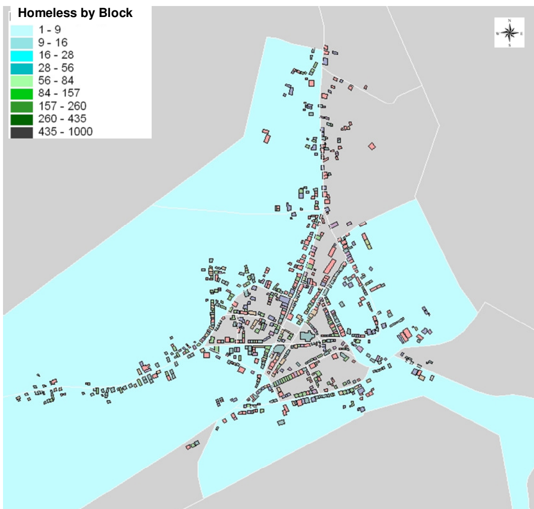

Figure 7: Homeless by block in São Sebastião (Terceira Island)

6. FINAL CONSIDERATIONS

A simulator capable of generating seismic scenarios was developed to produce losses to the population and to urban equipment. It is important provides individuals and community decision-makers with information to assess seismic risk, make informed decisions about seismic safety in their communities, and determine what can be done to mitigate risk

This project will be applied at a large scale to the entire stock of buildings in the Central Group and in detail to five urban areas (Lajes do Pico, Almagreira, Angra do Heroísmo, Praia da Vitória, S. Sebastião and Horta). This simulator requires further development taking into account recent data from Azores and Italian earthquakes in attenuation of seismic waves, site effects and vulnerability analysis. The simulator will also include analysis of landslides and liquefaction.

A comparison of results obtained with the simulator and the inventory of damage in recent earthquakes (1980 and 1998) will be made as a form to calibrate the model.

Through a global analysis (in terms of victims, costs, social economical impact, immaterial consequences, etc.), the weaker points of the urban systems in the Azores archipelago will be identified. After the risk analysis is important assess the interdependency of the activities, functions and human behaviour in an urban system.

The elements and urban infrastructures can be improved, if change its functional characteristics in accordance with the degree of risk of each element, per example, do not implement hospitals in liquefaction areas or construct an additional bridge in a strategically crossing, to facilitate the evacuation.

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