COMPARISON OF OBSERVED DAMAGE WITH RESULTS FROM ANALYTICAL SIMULATION MODELS. THE CASE OF JULY 9, 1998, FAIAL EARTHQUAKE IN THE AZORES.

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ABSTRACT :

The July 9, 1998 earthquake that struck Faial, Pico and São Jorge Islands in the Azores archipelago provided a large amount of information which permits the validation of damage scenarios simulators. Ten years later and integrated on the project FCT - POCI/CTE-GIN/58095/2004 “USuET –Urban System under Earthquake Threat”, we are able to recreate earthquake effects in the urban areas that comprise about 3000 buildings using data collected during the reconstruction period (1998-2007). Based on a post-inspection of building files, a database was compiled with typology classification, damage description, reconstruction techniques and costs of intervention.

For this stock of housing we developed a damage scenario simulator using the empirical vulnerability methods of the EMS-98 macroseismic scale as well as vulnerability obtained through mechanical modelling of a few typologies. The influence of the soil layers (geological and geomorphologic effects) were also taken into account as part of the attenuation process.

The aim of present article is to compare values, in terms of number of collapsed houses and mean damage grade obtained by the seismic simulator with those verified on July 9, 1998, and update the analytical models in order to reduce the error between model results and observed values.

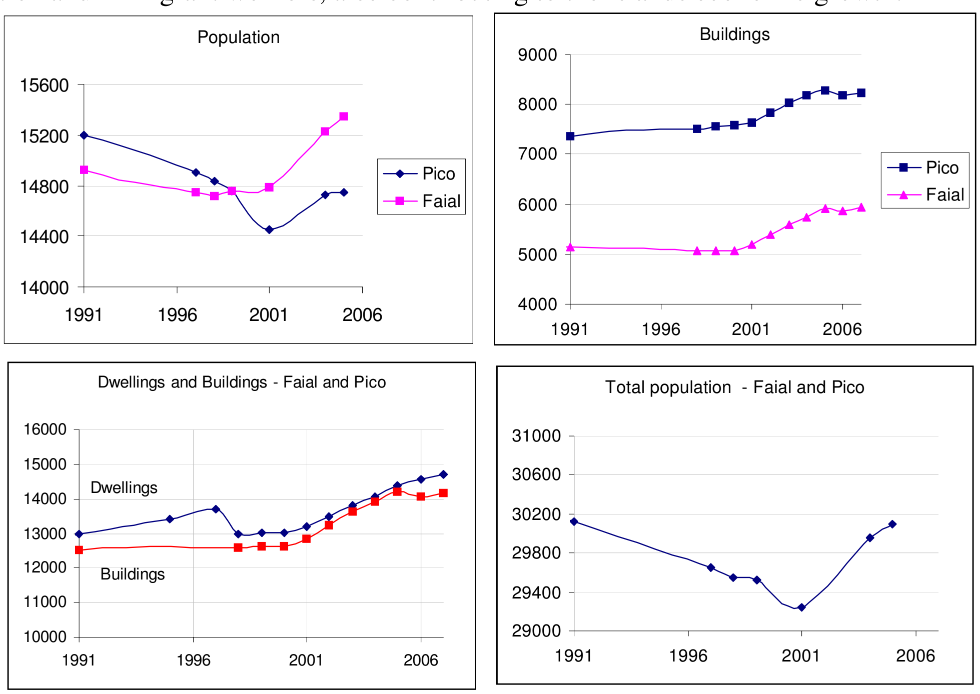
KEYWORDS: Azores, Damage , Simulator

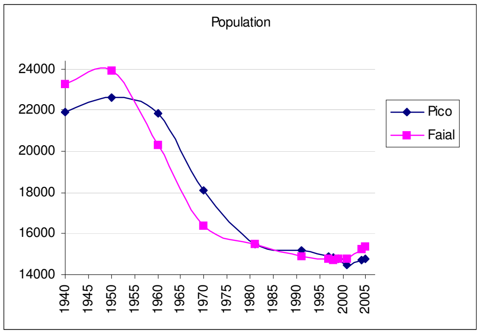
1. INTRODUCTION

The 1998 Faial earthquake which measured Mw 6.2 caused 8 deaths, hundred of injuries, 2500 homeless, 35% of the Faial buildings were affected and 10% in Pico (from slight damage to destruction) and a great impact on socio-economic activities occurred during a long period. The main annual event of the main city Horta (Semana do Mar - Sea Week in August) was cancelled as consequence of the earthquake, with a clearly social impact in the island. Today, ten years later, many things in Faial and Pico islands are different: increased the earthquake safety procedures for building construction, new urban areas, infrastructure and services were developed as well as some new urban planning measures were studied although an effective application was not yet implemented. The data collected during those years allowed the study of damage observed in masonry housings as well as were important to obtain some explanations about the seismic wave propagation.

2. POPULATION AND HOUSING STATISTICS

Totals of population and housing units of Faial and Pico islands are herein presented according to various Censuses. Figure 1 show the evolution of population and housing during the 60 years and illustrate a population decrease between 1950-2001 as the result of emigration caused by Capelinhos volcano eruption in 1957 and due to lack of employment on the islands which forced people to leave. Consequently, buildings have been abandoned during these years and an old and vulnerable housing stock was at stake, contributing to the high damages observed whenever an earthquake occur - due to structural deficiency in design and unsafe construction features. Figure 1 show also a moderate increase of the population and housing between 2001 and 2007 in part prompted by the process of reconstruction and rebuild after the 1998 earthquake, creating a large number of jobs for local population and immigrant workers, also contributing to the islands economic growth.





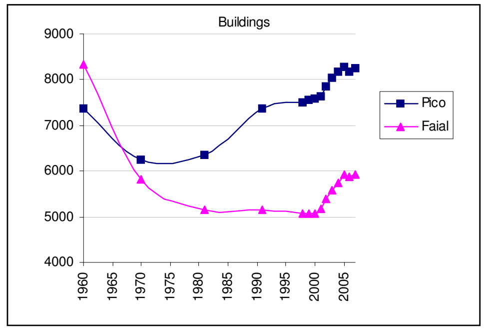


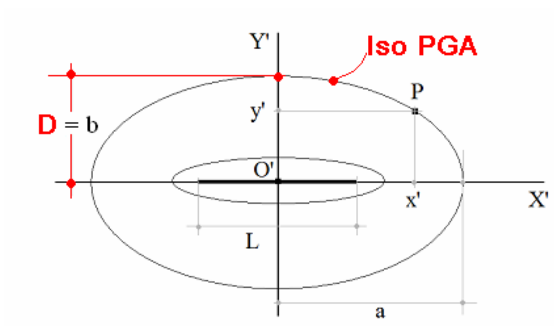
Figure 1 Evolution of population and housing between 1940 – 2007 (Ferreira and Oliveira, 2008)

3. THE 1998 FAIAL EARTHQUAKE

Azores archipelago located between the triple junction of three large tectonic plates (Eurasian, North American and African) is frequently subjected to seismic activity. The 1998 Faial earthquake, with epicentre 8 km NE of Faial island, caused major destruction in the north-eastern part of the island. The maximum felt intensity (Modified Mercalli Scale) in that part was VIII (Matias *et al*., 2007) and is influenced both by site effects related to thick layers of soft sediments and pyroclastic deposits, and by the high vulnerability of existing constructions.

3.1. Propagation of seismic waves

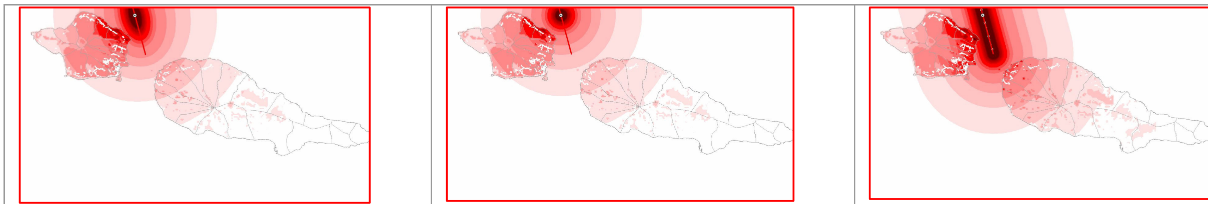
When modelling propagation of seismic waves in bedrock, a geometric parameter is usually considered in the attenuation law, using some functional form of distance to the seismogenic source. Typically, *distance to fault* or *distance to epicenter* is used. In this work a different approach was used, assuming that Peak Ground Accelerations (PGA) isolines were ellipses (Figure 2). These ellipses are centred in the epicenter, with the major axis coincident with the projection of the fault in the surface with eccentricity showing a logarithmic decrease with circular distance, achieving null value (ellipses turning into circles) about 20 km from epicenter.



$$\frac{x'^2}{b^2} + \frac{y'^2}{a^2} = 1 \; ; \qquad e = \sqrt{1 - \left(\frac{b}{a}\right)^2} \tag{3.1}$$

Figure 2 Elliptic propagation of seismic waves

Evaluation of *a* and *b* depend on the characteristics of the kinematics of fault rupture and were computed for the situation of 1998 earthquake to comply with the stochastic model methodology developed by Carvalho *et al.* (2004) and applied by Zonno *et al.* (2008) to this earthquake.
Figure 3 presents the three different approaches to the attenuation of seismic waves, the elliptic one proposed in this paper, the standard circular and the one considering the distance to the fault trace.



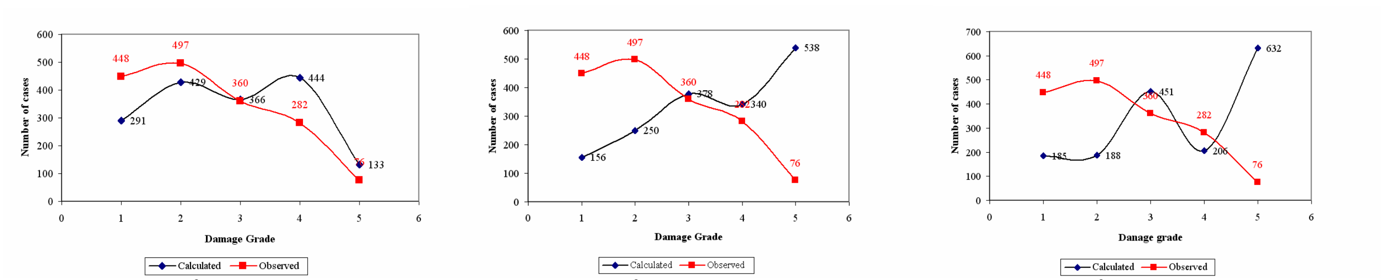
a) Iso PGA = Ellipse

b) Iso PGA = Distance to epicenter (Circular)

c) Iso PGA = Distance to Fault trace

Figure 3 Propagation of seismic waves: different approaches

An interesting conclusion with this model is that the error of the model using this approach was significantly lower than the one obtained with the other approaches. For that, we used Eqn. 3.1 to predict the expected damages in buildings, comparing these values with the observed ones. Then, frequencies of each damage grade were compared with the observed ones and χ^2 for these adjustments were obtained as illustrated next.
As we can see (Figure 4), the elliptic model was the one that showed better results.



χ^2=179
Eliptic Distance

χ^2=1198
Circular Distance

χ^2=1417
Distance to Fault

Figure 4 Propagation of seismic waves: different approaches

3.2. Using PGA to calculate damages

Models to derive expected damages in buildings, commonly use Macroseismic Intensities. This approach requires the selection of an appropriated expression, usually an empiric one, to transform PGA into Intensities (Trifunac and Brady, 1975), which is another not desirable source of uncertainty and error into the model. An alternative of such empirical approach is the use of Capacity Spectrum methodologies like HAZUS (FEMA, 1997). But this more sophisticated methodology, even though much more close to the physical process, it is also much more expensive, time consuming and, some experts argue that it requires an adequate calibration of too many parameters. This implies many analytical runs, experimental testing, etc.
In keeping it simpler we follow the first alternative dealing with Macroseismic Intensities. So, it would be interesting if we could use PGA directly to derive expected damage. In this respect we tried to adjust a LogNormal function (Eqn. 3.2) to describe expected damages and, surprisingly (or not) we obtained correlation coefficients near 1,0.

$$P[Ds \geq ds_i] = \mathbf{\Phi}\left[\frac{\ln(PGA) - \ln(X_i)}{\beta_i}\right];$$

$$\beta_i = m.\ln(X_i) + n; \qquad (3.2)$$

$$X_i = \mu(Gd, Vu) = a.Vu + b.\left[1 - e^{\left(c.\frac{Ds_i}{Vu}\right)}\right]$$

where:

$P[Ds \geq ds_i]$……defines Fragility of a class of buildings with Vulnerability Vu.
Φ………….. is the cumulative Normal Distribution (parameters *m, n, a, b* and *c* dependent on coefficients used in Eqn. 3.3).

3.3. Intensity = f (Vulnerability and Observed Damages)
If we have Ds = f (Vu, I) why not try to derive *I = f (Vu, Ds)?* In fact, if we could use a systematic and less subjective way to *Observe Intensities*, we would have more systematic and uniform observations, helping the comparison of data collected by different people and sources. As proposed in Giovinazzi and Lagomarsino (2004) and Bernardini *et al.* (2007), by Eqn. 3.3 we can derive Mean Damage Grades (μ_D) from Observed Intensity I, and Vulnerability Vu associated with each building typology. But this equation is difficult, if not impossible to invert. However, Eqn. 3.4, which provides exactly the same results, is easily invertible, and by doing this we arrive at Eqn. 3.5 which provides what we aimed at.

$$\mu_D = \left[2,5 + 3.Tanh\left(\frac{I + 6,25.Vu - 12,7}{3}\right)\right].\begin{cases} e^{\frac{Vu}{2}(I-7)} & If\ \ I \leq 7 \\ 1 & If\ \ I > 7 \end{cases} \tag{3.3}$$

$$\mu_D = 2,454.\left[1 + Tanh\left(\frac{I + 5,493.Vu - 12,076}{1,758}\right)\right] \tag{3.4}$$

$$I = 12,076 - 5,493.Vu - 1,758.Tanh(1 - 0,407498.\mu_D) \tag{3.5}$$

Using such an approach, we have a systematic and uniform way of obtaining Intensities, which helps in controlling and minimizing sources of errors in the models. In the present case, a GIS platform was used to compute μ_D from *Vu* and, from there, Intensities can be derived and mapped to compare with values proposed by other authors. *Vu* were determined for different typologies existing in Faial and the damage grades to individual buildings determined by inspection based on the data-base from the Reconstruction Process (Ferreira and Oliveira, 2008).

3.4. The Crystal Buildings
The most surprising observation came from the *fragility* values of traditional buildings. Their typology, characterized by stone masonry with wooden floors and wooden roof, showed a very different behaviour from the one expected from EMS-98. In fact, those buildings, as observed now (Figure 4), sustained well the low to moderate Peak Ground Accelerations, PGA's, with no observed damages, until the point where they suddenly collapse. We could say that we are in presence of *Crystal Buildings*. With this *fragile* behaviour to the seismic action, they do not conform with fragility derived from EMS-98, nor with macroseismic models based on that scale. In fact, EMS-98 sustain that in areas of Intensity VI, more then 60% of Masonry buildings are expected to show damage grades greater or equal to ≥1. In this case, it was observed that for this low intensity zones, with PGA's from 0,1g to 0,2g, only about 6% to 13% of these buildings suffered some kind of damage. In the other side of the scale, in zones of Intensities VIII, with PGA's in the range of 0,6g to 0,7g, observed on the NE of Faial, next to the fault, EMS-98 indicates that about 5% of these buildings are expected to collapse. The observed data showed that here, 13% to 40% of these buildings have collapsed. It is interesting to note the observation found in Costa *et al.* (2008) about the behaviour of a tested stone masonry specimen, representative of this typologies: "*The energy dissipated by the experiment during the test was significant but with significant deterioration of the specimen, leading to a severe loss of strength for the same displacement level*".

4. FINAL CONSIDERATIONS

The model presented will be in the future compared with real data from observed damage, case by case and by grouping in geographical units and with macroseismic intensities proposed by different authors.

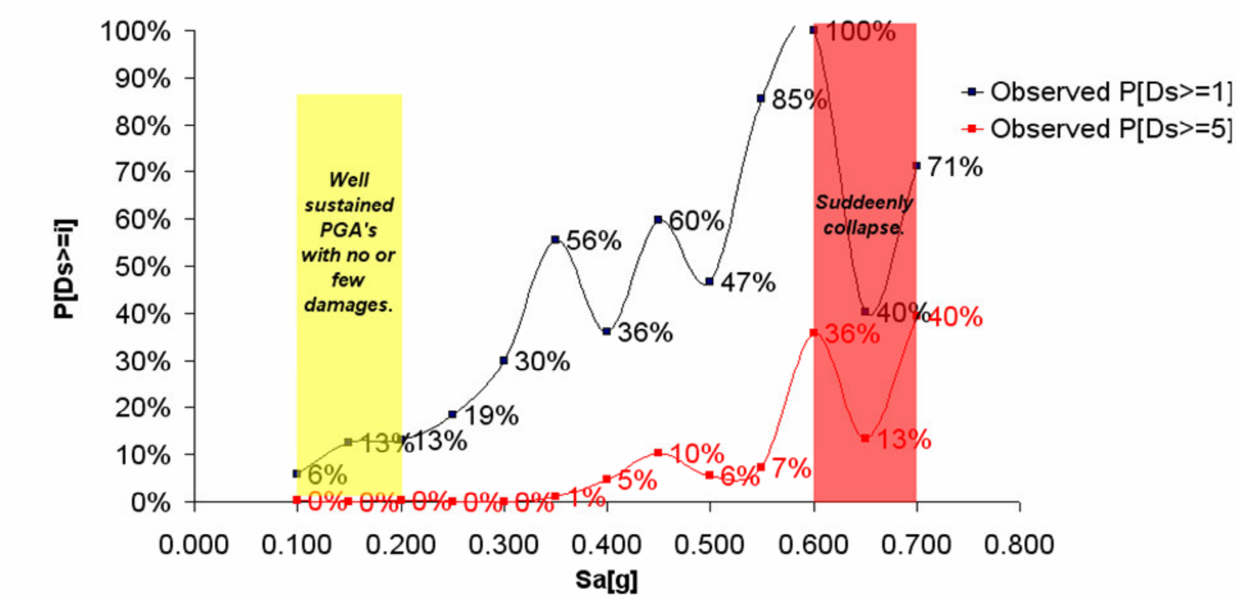


Figure 4 Observed fragility of Traditional Buildings in the Azores

5. ACKNOWLEDGMENTS

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