

# Seismic Vulnerability and Impact Analysis: Elements for Mitigation Policies

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**ABSTRACT:** As an introductory part, a brief description on the effects of earthquakes on the built environment since 1900 is presented, first for the entire world, then for Europe and for Portugal. Attention is called for the non-stationary character of earthquake catastrophes, with periods of very high human losses contrasting with quiet periods. An analysis of the main causes for damages, victims, injuries and homeless is presented based on statistical data collected. Elements for the mitigation of earthquake risks through the use of scenario simulators in a GIS environment are briefly summarised. Among the various problems encountered we will concentrate on three main points: (i) seismicity of Portugal showing the uncertainties on source-propagation models; (ii) structural characterization of two types of masonry buildings; and (iii) the seismic impact in Faro, south of Portugal. For this purpose, an account of the main events occurred in the area of influence for Faro is made, together with a description of the tectonic environment of the region, including the alternative models for the 1755 earthquake. A comparison of three different methods for estimating earthquake vulnerability of the building stock at an urban area based on the EMS-98 is presented. The first method makes the interpretation of EMS-98 scale using Fuzzy Set theory (Giovinazzi and Lagomarsino, 2003); the second method uses the multi-criteria Macbeth algorithm (Bana e Costa and Vansnick, 1997); and the third method uses simple statistics considering only expected values. These models were applied to the city of Faro, in the continuation of a preliminary study presented in this Congress, Oliveira *et al.* (2004).

## 1 EARTHQUAKES IN THE WORLD AND IN EUROPE SINCE 1900

A simplified analysis of the evolution of human casualties and economic losses all around the world caused by the seismic activity since 1900 (Figures 1 and 2), clearly indicates a steady increase of economic losses (Figure 3), especially in the last decade. In fact, while casualty figures oscillate around the 190 000 per decade (in a total of 1.9 million) and are marked by the occurrence of very large events (Japan, Kwant, 1923, China, 1920, etc., in the decade 1920-30 and Tangshan, China, 1976, decade 1970-80), the economic losses, corrected to the year 1997, show an exponential increase. Such increase can be attributed to earthquakes striking regions of high urban concentration, for which no seismic protection has been implemented due to difficulty in transferring of technology to the construction industry.

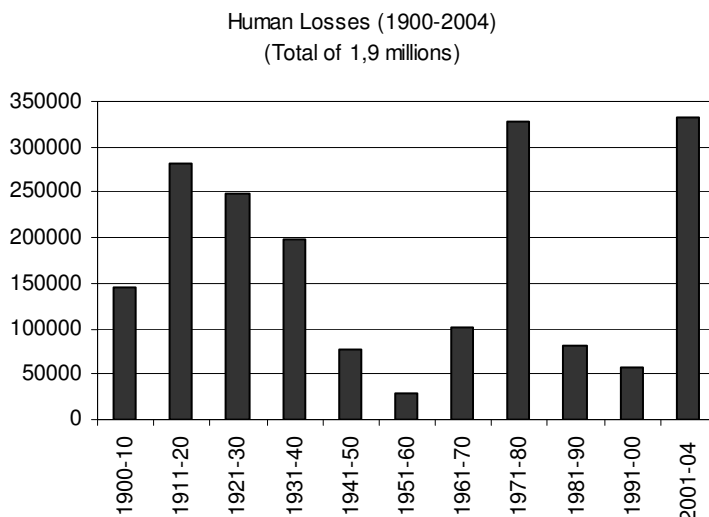


Figure 1 - Human losses (1900-2004)

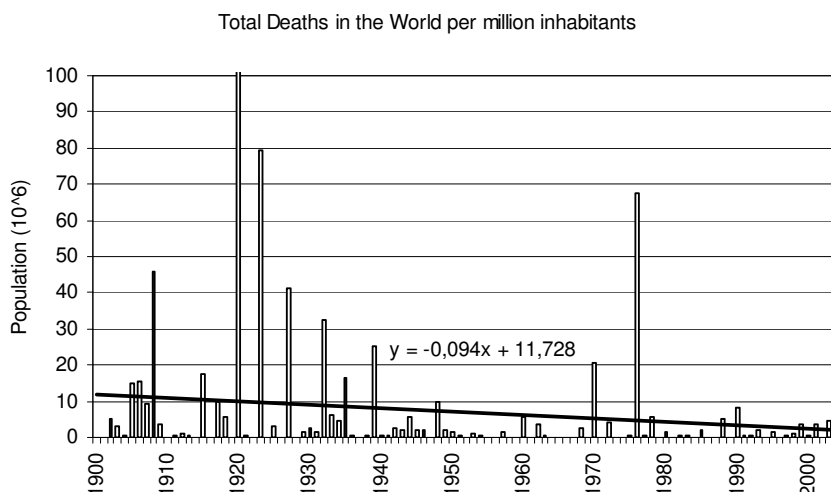


Figure 2 - Total deaths in the world per million inhabitants (1900-2004)

Figure 2 indicates periods of very high human losses contrasting with quiet periods. This is because urban earthquake risk in poor countries is large and rapidly growing. Today, there are five times as many people in poor as in rich earthquake-threatened cities. This fact, associated with poorly constructed concrete-frame structures, lack of land-use planning and methods of emergency response planning, and lack of information and investments in disaster mitigation increase the number of deaths in developing areas. The 1988 Armenia earthquake and the 1989 Loma Prieta earthquake in Northern California were nearly equivalent in their magnitudes and in the number of people occupying the affected regions, but the results were far different - 62 people died in California while at least 25 000 died in Armenia.

Even though great advances in seismology and earthquake engineering have been acquired in the last 20 years, a great deal of implementation is still missing. Many international organizations have spoken out for this problem, but results from these campaigns are still difficult to judge. It is worth noting that the same pattern of damage (human and economical) has been observed in the first years of the XXI<sup>th</sup> century. The December 26, 2004 M9.0 Sumatra earthquake with a terrible 300 000 victims caused by a huge tsunami has brought up the discussion on the importance of prediction on the medium-long term and the need for a real prevention. This prevention includes the launching of effective alerts that can reach the population and the critical facilities and the need for a structure reinforcing policy for the most vulnerable construction. The case of the Sumatra tsunami was "failure in terms of prevention"

that needs to be analyzed in all the aspects from seismology, engineering and preparedness in order that in the near future science, technology and politics can work together minimizing significantly the suffering of populations exposed to these hazards.

Two cases of success for the medium-long range earthquake estimation and the preparation for an announced earthquake are referred as examples to follow.

In the 1980's several researchers have brought to the scientific community their studies, indicating possible forecasts of important events. The well publicized case of Peru in the eighties was never given great attention by the scientific community. But the case of Parkfield in the San Andreas fault was seriously adopted by senior researchers to be used as a laboratory to measure physical parameters to be correlated with the occurrence of the earthquake. Unfortunately, the predicted event only took place at a time much off the mean predicted value. Figure 3 shows the sequence of 5 events occurred in the region and the last one (2004) that breaks the "good behaviour" of the fault.

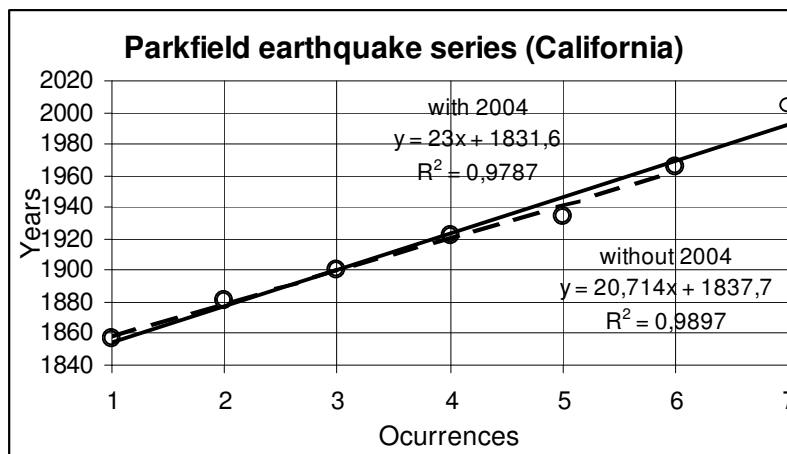


Figure 3 - Parkfield sequence of events. An announced prediction: 2004 (EERI web page, 2004)

Other elaborated methods as the ones developed by Keilis-Borok and his colleagues at Moscow are interesting tools capable of detecting patterns in the earthquake activity as far as times and locations of very large events are concerned. However, the estimative for future activity lead to such large time and space windows that predictions become of low interest for the populations and authorities of the affected regions.

The second case of good success was the evaluation of the potential slip along the fault for the Trans-Alaska Pipeline System. During the 2002 Denali M7.9 earthquake the design slip to account for the crossing portion of the pipeline was slightly over passed, causing minor damage to support systems.

As far as prevention is concerned, the announced large event with large probability to occur within 30 years nearby the metropolitan area of Istanbul has launched a campaign for a Master plan execution (Erdik and Fahjan, 2005).

Even in the case of precise prediction at short term (days or weeks) which would save human lives by moving the population to safer places, economical losses would not be avoided because the impossibility to protect the structures and the economical tissue at such short notice.

Looking to the economical losses for the XX<sup>th</sup> century with values normalized to 1997, Figure 4, we can see that the pattern is of an almost constant steadily increase in time with a log scale trend. This significant increase is the result of seismic activity affecting developed countries where the potential for moderate to strong damage is quite important.

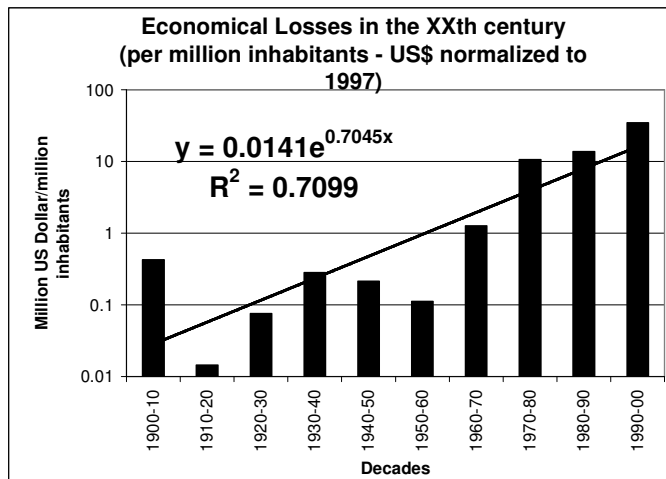


Figure 4 - Economical losses in the world during the XX<sup>th</sup> century

In relation to earthquake risk, it is interesting to analyse the tendency to divide the political world into two large geographic areas: the world of poor countries and the world of rich countries. For the former ones, human casualties are increasing throughout the century and are one order of magnitude above the rich countries, whereas, for these ones, the opposite tendency is observed when dealing with economic losses. On the other hand, it should be important to emphasize that in the last decade of the XX<sup>th</sup> century very large events took place with catastrophic consequences, both in human and in economic terms. Considering only the six earthquakes with magnitudes in the range 6.7 to 7.5, human casualties attained more than 70 000 and losses were above  $150.000 \times 10^6$  Euros.

Looking in a more detailed way to the economic losses, the Kobe 1995 earthquake alone was responsible for more than  $100 \times 10^9$  Euros, which is equivalent to almost 2% of the Japanese Gross National Product (GNP). This earthquake affected 3.6 million inhabitants from a total of 4.5 million residents in the region, causing 5500 casualties and 41 000 injures, important damage to 3500 buildings in reinforced concrete and steel, and destroying around 80 000 dwellings. These incredible numbers when transferred to other regions such as the metropolitan area of Lisbon, with a slight smaller population, would cause losses of the order of the Portuguese GNP.

The Northridge 1994 earthquake caused about one third of the Kobe losses, but economic loss estimation corresponding to the repetition of the Kwant (Tokyo) 1923 earthquake would surpass, in an order of magnitude, those numbers.

The XX<sup>th</sup> century has finished with two very large events with magnitude greater than 7.5, separated in time by just less than a month. The Kocaeli earthquake in Turkey occurred in August 1999 and caused tremendous impact in the area east of Istanbul. Over 17 000 people were killed, about 44 000 were injured and 500 000 people become homeless. About 120 000 buildings and houses were considered beyond repair, among which about 5000 were seriously damaged or completely collapsed. The total economic impact of this earthquake is still difficult to establish. The second event, the Chi-Chi earthquake of September 1999, affected a large area of Taiwan causing over 2000 deaths and an economical impact of the order of  $3.2 \times 10^9$  Euros.

Whatever location around the world, the impact of earthquake activity is so large that, in recent years, a great concern has led to the development of impact studies in large metropolitan areas such as Mexico City, Tokyo, San Francisco, Istanbul, Bogotá, etc. These studies, known as scenario evaluations for Megacities, are essential tools for several different applications, which run from simple evaluations of earthquake risks, to exercises for civil protection, indications for insurance companies, and re-evaluations of mitigation measures.

Earthquake activity in time and space for a given region is not well known and cycles with certain stability can be interrupted by other type of cycles. In recent times, large earthquakes occurred in regions where no historical evidence was present. The cases of Kobe and Athens earthquakes in 1995 and 1999, respectively, are among these events occurring in regions of low seismicity. A great discussion was initiated on the reliability of hazard methods, which cannot

present good results if long period observations are not taken into consideration. To avoid such difficulties, studies including paleo-seismology and arqueo-seismology information should be made for regions where long return period activity is suspected.

In 1980, a terrible earthquake struck southern Italy, killing 4 600 people and leaving 250 000 homeless. More recently, in 1999, the Kocaeli earthquake in Turkey caused extensive damage and human suffering.

There have always been earthquakes. Damage seems greater today for two reasons. First of all, countries are more densely populated, including those at risk. Secondly, there is new industrial infrastructure that may be vulnerable in the event of an earthquake: gas and oil pipelines, dams, chemical factories and so on.

The lack of regularity in the pattern of earthquake activity has been a characteristic of the seismic activity in Europe, Figure 5, especially in the large area running from the Azores to the Greek islands, in the neighbouring of the Euro-Asiatic and African plates. With the exclusion of Greece, no event with magnitude larger than 5.8 was recorded in that area from 1920 till 1980. In the year of 1980, three larger events occurred: in the Azores (Jan, 1<sup>st</sup>), in El Asnam Algeria (Oct 10<sup>th</sup>), and in Irpinia, south Italy (Nov 23<sup>th</sup>). Since then, the most important events occurred in Algeria (1994) and in Italy (1997), the latter causing great impact over the historical heritage in the centre of Italy (<http://emidius.itim.mi.cnr.it/>, 1997, 1998). In summary, one can say that, in the period 1980 to 1995, about 5000 people lost their lives in the territory of the European Union due to earthquake activity leading to a total economic loss above  $430 \times 10^6$  Euros (Ghazi *et al.*, 1997). It should be mentioned that most catastrophic event in recent times for the European population was the Sumatra earthquake, 26 December 2004, whose tsunami caused more than 4000 victims in tourism.

Total Deaths in Europe

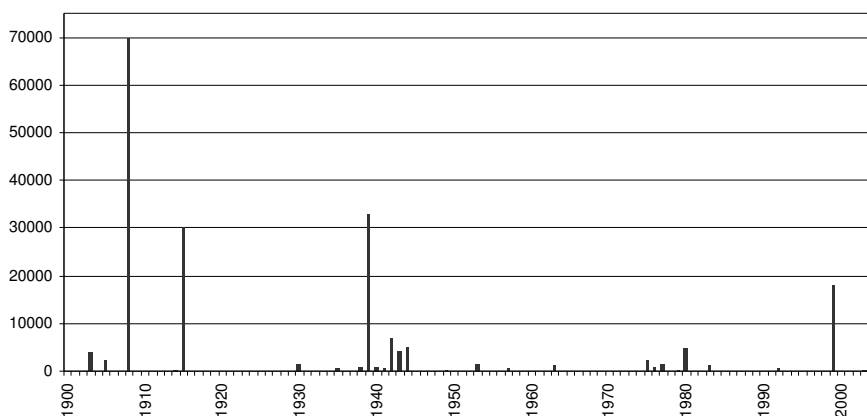


Figure 5 - Total deaths in Europe (1900-2004)

In the topic of natural catastrophes, earthquakes play a very important role, world-wide. As a matter of fact, statistics taken from the period 1973-1997 (<http://www.cred.be>), organized by 5-year bins, show that earthquakes are among the disasters with larger death impact, even though the total number of flood events is twice per year.

This analysis on the effects of earthquakes on the built environment can be traced for the entire XX<sup>th</sup> century. This calls the attention to the communities that seismic risk has been increasing along the times in spite of all the great advancements achieved in scientific and technical grounds. Problems of bad use of "good engineering knowledge" and lack of quality control are behind these poor results.

Figure 6 represents the number of deaths versus magnitude. In gross terms we can say that the developing regions tend to lie on the upper side of the diagram whereas the developed regions are in general towards the lower side. An effort to reduce the number of deaths in developing countries should be a first world-wide priority; the economical losses occurring in developing countries constitute the other important policy to follow.

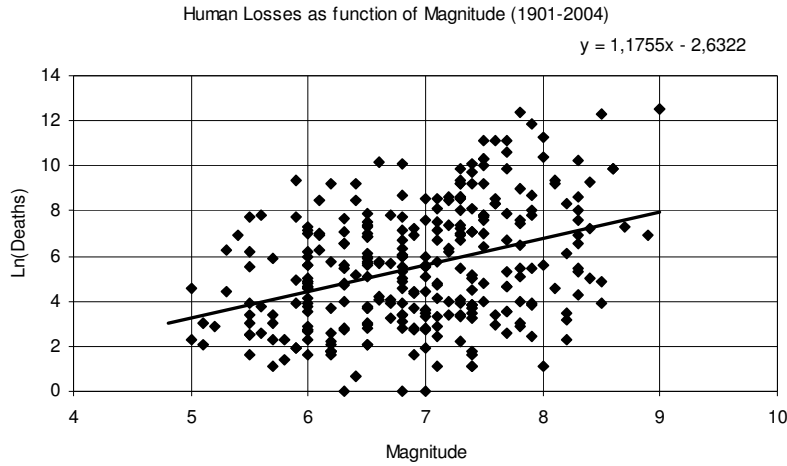


Figure 6 - Number of deaths versus magnitude (Note: the ordinates are logarithm neperian of number of deaths)

The next Figures 7 and 8 show the correlation between death and injuries and homeless and injuries, which give a good perspective on how the society can expect to have their major impacts.

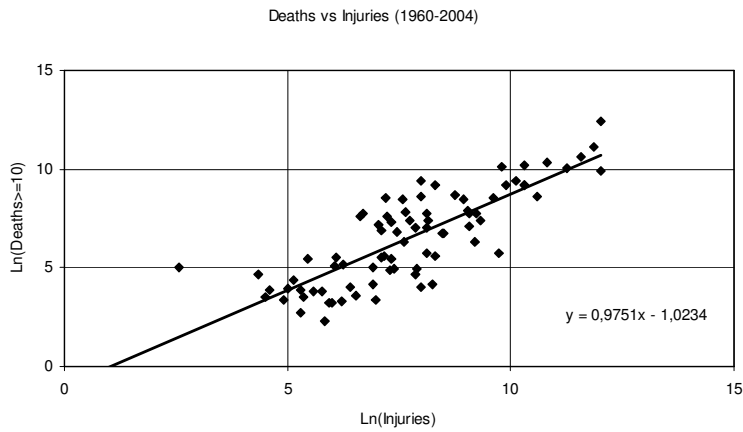


Figure 7 - Number of deaths versus number of injuries (Note: the ordinates are logarithm neperian)

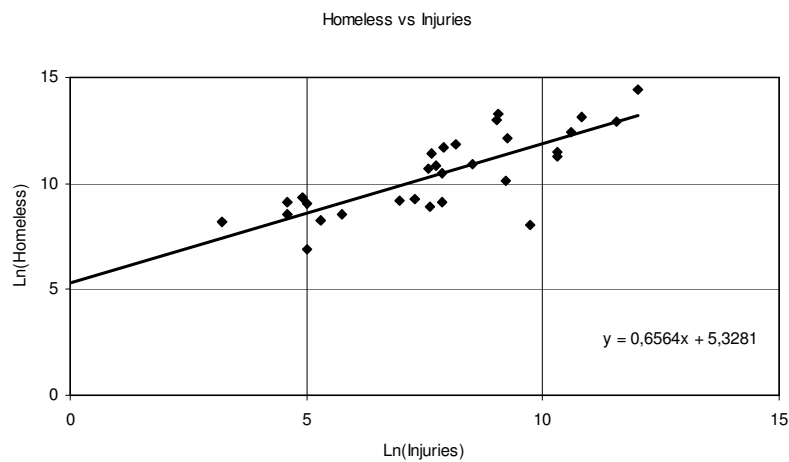


Figure 8 - Number of homeless versus number of injuries (Note: the ordinates are logarithm neperian)

The estimation of human casualties is a difficult and complex task. Several authors (Tiedemann, 1992, Bramerini *et al.*, 1995, Hazus, 1999, Coburn *et al.*, 2002, etc.), have proposed formulae to compute the casualties based on intensity values, degree of damage inflicted, trapped population, etc. Unfortunately, those formulae were based on data of single events prior to 1990, not reflecting data from the most recent events. In Figure 9 the total number of people killed is plotted against the total number of buildings severely damaged in earthquakes (Coburn *et al.*, 2002). An approach to estimating these casualties is by defining the building typology and determining the ratio of the number of people killed to the number of occupants present in collapsed buildings of that class of typology. Further works and research, using data from recent events, should be done in order to obtain more realistic numbers. It is important to study the relationship between the attributes of urban areas and casualties in order to reduce the casualties. Although the principal cause of human casualty and deaths is the collapse of the buildings, there are a wide range of other "urban causes", like medical conditions, fires that occurred after earthquake, capacity of transportation and rescue, etc. that should be used to estimate the number of deaths, injuries and homeless.

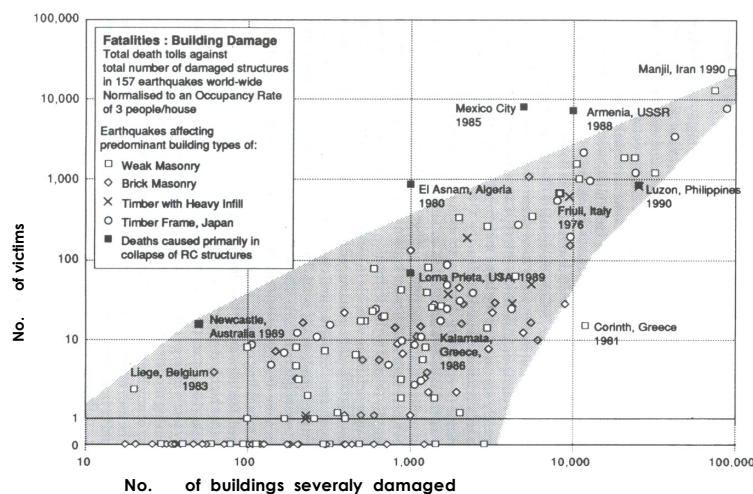


Figure 9 - Dispersion in estimating the number of victims (Coburn and Spence, 2002)

## 2 ELEMENTS OF SOCIETY AT RISK AND OVERALL IMPACT ESTIMATION

The elements of society at risk considered for impact studies due to a serious seismic action are several. The detail of analysis, both of the elements at risk and of the methodologies to be followed depend very much on the scale of work. For a discussion of the different approaches that apply to each case see Oliveira (2004a). A summary of the main items and the methodologies to be considered are mentioned below. Alternative method for the vulnerability analysis based on the EMS-98 description following the main ideas proposed by Giovinazzi and Lagomarsino (2003 and 2004) are presented at a separated later chapter.

### 2.1 Identification and characterization of elements of society at risk (vulnerability identification)

The elements of society in risk considered for impact studies are the ones which can be seriously affected, causing human life loss and society disruption, some times for a long period of time. The vulnerable elements to be considered are:

- Population (producing death, injures of various kinds, and homeless);
- Building stock and industrial plants (dwelling with partial or total collapse);
- Lifelines: roadways; railways, including the subway; energy (electricity, gas, and other combustibles); water; sewerage and telecommunications (disturbing seriously the social tissue due to operation collapse, temporarily malfunction, etc.);

- Vital (those that are relevant for emergency management, either due to its operational or political role) or important structures (due the consequences of malfunction or collapse).

## 2.2 *Establishment of seismic occurrence scenarios*

The establishment of feasible scenarios requires the study of past seismic occurrences, the definition of different seismogenic zones affecting the area under study, and the characterisation of their most important parameters (maximum expected magnitude and frequency or probability). It may also involve the knowledge of attenuation functions, if scenarios have to do anything with ground motion parameters, or the minimization of any other objective function, as total losses inflicted within a given time period.

In many applications not only one single criterion prevails. Hypotheses to be analysed are: the consideration of a largest historical event, as a measure of an extreme type event; the 50, 100 or 1000-year mean return period event, requiring an hazard and disaggregation analysis; the most probable measure of impact over the entire stock in the study area; or the eventual rupture of a possible fault structure.

## 2.3 *Propagation of seismic energy*

The release of seismic energy from their different possible sources (seismo-tectonic structures) and its propagation through the crustal Earth layers to the bedrock underneath the site under analysis is generally considered as the attenuation of seismic waves. Local effects representing the transference of energy from bed-rock through the upper soils, with the potential for ground motion amplification or reduction, liquefaction and land-slide potential, are consequences of soil properties and characteristics of input ground motion (level and energy content).

Several techniques can be used in the context of propagation of seismic waves, ranging from peak ground values (acceleration - PGA, velocity - PGV or displacement - PGD), spectral values, or seismic intensities (Mercalli Modified intensities - MMI, European Macroseismic Scale - EMS-98, etc.). Primarily they relate these values with magnitude and epicentral distance and, in the case of better tectonic definition, also with other source parameters.

This task is of great importance to reduce uncertainties in the entire process of impact estimation. Existing data from past earthquakes, even of small magnitude values, should exercise the calibration of attenuation relationships.

## 2.4 *The soil effect*

An alternative way to this procedure is to use the concepts developed in the recent codes for definition of seismic action, such as the approved version of Eurocode-8, where soils are classified in great detail covering most common situations observed in many different regions. Ground motion in terms of response spectra for each soil class at the surface is also given, consequently avoiding the difficult part of analysing the wave propagation within the soil layers. In this respect, the information leading to the proposed spectra was supported in a large collection of strong motion data recorded at the top of the various types of soil profiles. US policies through recent UBC97 legislation (FEMA, 1997, SEAOC, 1995) also consider a variety of soil classes, which can be used in connection to the type of studies under analysis.

## 2.5 *Vulnerability evaluation*

The vulnerability of each element at risk is analysed using functions that relate the expected damages of each type of element with its characteristics and subjected to the seismic action acting at the foundation level.

The building stock is statistically analysed having as reference the unit depending on the scale of work (corresponding for instance to single building or to the smallest administrative territorial division) and a diversity of parameters of the buildings such as age, constructive typology, number of floors, etc. Several techniques have been developed to derive these vulnerability functions, from simple curves taken from observed behaviour during past earthquakes (the so-called *probability damage matrices*), to complex engineered structured



response analyses, or directly obtained from definitions of intensity scales. Several typologies have been developed to consider the seismic behaviour. Here, again, depending on the scale of work and on the knowledge on individual units, building typologies range from 5 or 6 main categories (essentially by epoch of construction and attending to the type of material) to a detailed analysis with a few dozen cases (detailed construction types within, for instance, the reinforced concrete (RC) group of buildings), as referred in the *Hazus 99* (1999) proposal.

A similar methodology has been adopted when dealing with lifelines, by classifying them according to types, materials, geometries, epoch of construction, etc., and defining the corresponding vulnerability functions. For emergency planning purposes, the results of each lifeline damage estimation, for each scenario, aims at a quick preliminary restoration, in order to assure basic indispensable services.

To estimate the impact of earthquakes on the human life, it is indispensable to characterise the demographic distribution for different periods of the day and around the year. Not only the population living within the study area, but also the population commuting to/from other adjacent areas, is of utmost importance to define their geographical location at the time of the seismic event.

Vital or important structures have to be identified, and their vulnerability functions need to be attributed. This is a very difficult task because only an individual detailed study can more effectively produce reliable results, requiring the participation of the entities responsible for them. The use of vulnerability functions adapted from the general building stock case has been commonly practised in impact studies, increasing the errors associated with their evaluations. One policy to follow is to separate these structures in large groups such as hospitals, schools, places of great concentration of population, structures of historical value, etc., and initiate a detailed vulnerability study of each group. In this way, uncertainties will decrease significantly and we will be close to reality.

## 2.6 *Damage evaluation for the established scenarios*

The evaluation of damages of the selected elements in risk, for each scenario, is obtained using a simulation model that integrates all the above mentioned aspects, by summing up all possible contributions. The damages of each element in risk are classified in several different limit states, usually defined at five levels: no damage, slight damage, moderate damage, heavy damage, and collapse. Depending on the element under study, this damage classification may be lumped into coarser categories or adapted to operational/non-operational terms, as in the case of sections of lifelines, etc.

For a rapid visualisation and treatment of all information, Geographical Information Systems (GIS) techniques are generally used. This requires a great deal of effort due to the need of digital vectorization of many layers, but is of great benefit for future applications, updating, corrections, alteration of algorithms, etc.

The GIS allows the visualisation of all types of variables organized by "layers". Examples of these are: intermediate results such as the geographical distribution of characteristic motion parameters (maximum acceleration, response spectra, etc.), either for bedrock and soils (local effects); the intensity distribution (Mercalli, EMS, etc.); any damage category for any specific layer, etc. It can be made at the work-unit level or can aggregate various units, depending on the objective pursued. Smoothing can also be applied for geographical interpretation. At the same time statistical analyses, cross-references, etc., are easily obtained with any standard statistical package.

Scenario studies are viewed in different perspectives according to the objectives to be targeted. These define the scale of intervention which is very critical in the way to obtain the elements necessary for the analysis. In this overview, special attention is given to the problem of scale, with the presentation of impact studies at four different scales: (i) scale of a country or large region, on the order 1: 1 000 000; (ii) scale of a region, 1: 25 000; (iii) scale of a city or of a block, 1: 5 000; and (iv) scale of a large building, 1: 1 000.

GIS techniques can combine different scales, but the accuracy of final results is determined by the one with poorer geographical detail.

## 2.7 Application Cases

In the application case presented we follow the methods showed in Oliveira *et al.*, 2004, which give most attention to the effect of scale in the treatment of the elements at risk.

Data and results are part of a GIS environment, where the various types of input data are treated, algorithms are developed and output results are statistical and graphically presented. This GIS operates as a "simulator", which for a given seismic occurrence characterized by the time, the magnitude and the epicentral location, produces a set of output functions such as EMS-98 intensity values, damage buildings and population affected. The model considers a simple attenuation law and the influence of the soil layers to estimate the seismic intensities at any location of the territory under analysis. Source-soil-and-structural influence is incorporated through the knowledge of predominant frequencies of the source process (function of magnitude), and of the natural frequencies of soil layers and buildings. The proximity of the various frequencies, introducing the resonance principle for amplification of seismic waves is developed in a simple way and indirectly expressed into the EMS-98 intensity. The study is made either building by building characterized through a detailed field enquiry or also based on blocks of buildings grouped into statistical sub-sections with data from census tracks (2001). The influence of scale of analysis is viewed for those cases. In order to better comprehend the structural performance of a few old masonry structures under seismic loads, a brief description of these structural systems is made and a simple analytical model presented.

Calibration of model properties is made with the use of *in-situ* measurements of ambient noise.

In the present work we emphasise the analysis of vulnerability based on EMS-98 interpretation, using three algorithms taken from the basic model of Giovinazzi and Lagomarsino (2002 and 2003).

## 3 SEISMICITY OF PORTUGAL

The seismicity of Portugal is moderate to strong, alternating periods of large events with long periods of quiescence (Oliveira *et al.*, 2002). In fact, periods of long quiescence alternate with periods of great activity. From the end of the XIX<sup>th</sup> century to the second decade of the XX<sup>th</sup> century a high rate of activity was observed throughout the country, with the occurrence the Benavente M=6.3 earthquake in 1909, followed by an enormous number of aftershocks. Since then, approximately 80 years of very low seismic activity have passed, only interrupted by two isolated episodes, one large M=8.0 event in 1941 with epicentre mid distance between the Azores and the Continent, and a M=7.2 event in 1969, in the Gorringe Bank, near the most seismic active interplate region SW of the Continent.

Figures 10 and 11 present a general view of the more active zones of the surrounded area, showing the geodynamic and seismological environments, respectively.

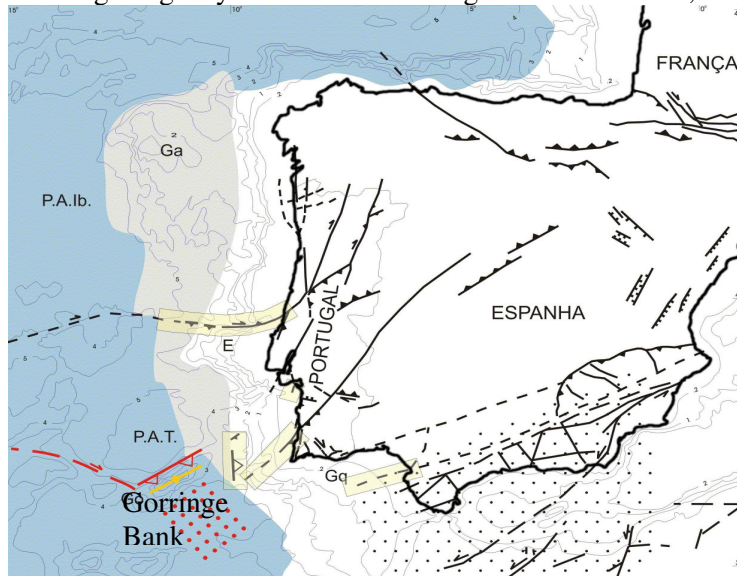


Figure 10 - Geodynamic environment for Continental Portugal (after Cabral, 1993)

Western Portugal is the locus of important intraplate seismicity, with destructive earthquakes in 1531, 1858 and 1909. These are events related to the Lower Tagus River fault structure.

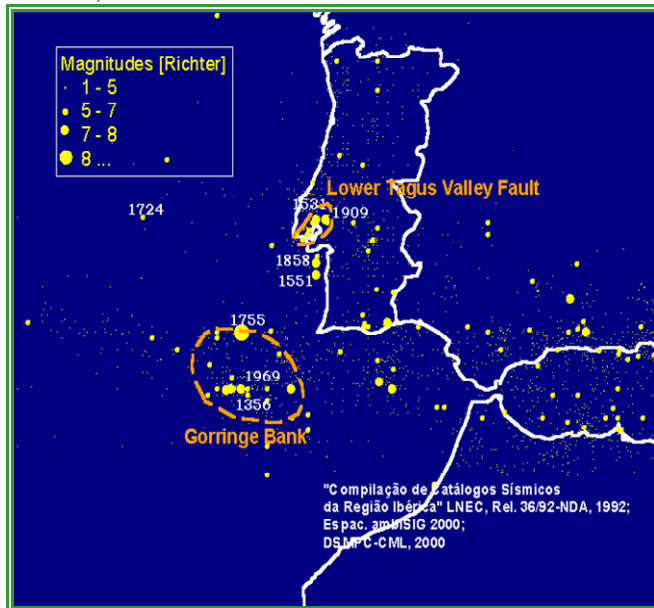


Figure 11 - Most important earthquakes occurred during the last millennium

The most active area is, however, the southern region in the transition between the oceanic and the continental crust. In this area of collision we have occurrences in 1356, 1755 and, more recently, in 1969.

The present seismic activity (in the last 5 years), monitored by the Portuguese Seismological Network, Figure 12, shows a wide spread of epicenters throughout the entire country with a few spots with slightly higher concentration of events. There is no apparent correlation of epicentral location with fault traces inland and alignments in the ocean with the bathymetric morphology, Figure 13. This is probably due to lack of high density of seismic stations and the difficulty in the precise location of epicenters in the ocean. However, for the first time, this more accurate data reveal the presence of important patterns, which, together with the campaigns of seismic prospections in the south and southwest Portugal, are producing the most significant piece of evidence for the seismic mechanisms related to the large historical events in this region.

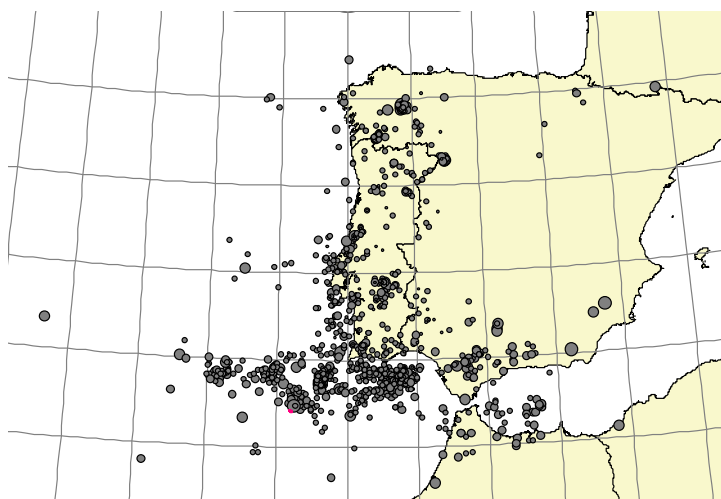


Figure 12 - Best located epicenters (1998-2003), Carrilho *et al.*, 2004

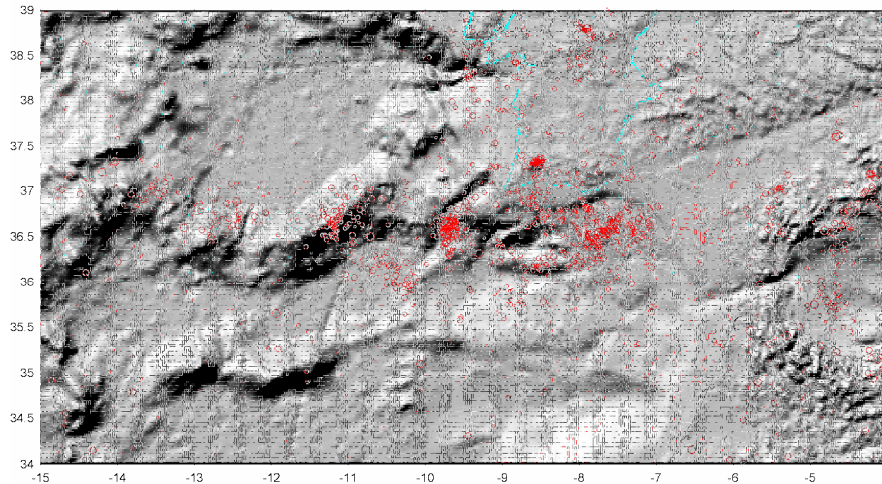


Figure 13 - Seismicity in south Continental Portugal (1995-2002) – Digital model of the Atlantic Ocean, Carrilho *et al.*, 2004

The probability of occurrence of events in Portugal, separated by main regions, is expressed in Figure 14, showing that the Gorringe area is by far the most active, with larger magnitudes exhibiting large return periods. Paleo-seismicity may constrain the information these data.

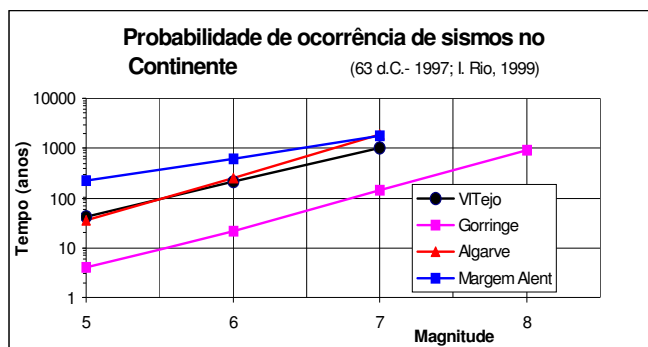


Figure 14 - Probability of seismic occurrence in Continental Portugal (according to Rio, 1999)

### 3.1 The 1755 Lisbon Earthquake: source models

The 1755 Lisbon Earthquake ( $M=8.6$ ) is one of the largest events known, damaging severely a wide area (which includes the Iberian Peninsula and the Atlantic Coast of Morocco) and causing a destructive tsunami, Figure 15. Lisbon was almost completely destroyed by the (i) shaking, (ii) by the tsunamis that invaded the downtown and dragged many people to the river and (iii) by the fire that lasted for 5/6 days. A total between 8 000 to 12 000 people may have died in a total Lisbon population of around 150 000. Numbers in southern Spain are in the order of 1200 victims and in other cities of southern Portugal are being revised. Great uncertainties do still exist for Morocco.

This was one of the most devastating events in Europe's history, illustrating the potential for low frequency, high magnitude events in Portugal.

The epicentre location and source mechanism of this event is still of great controversy. Figure 16 a) presents the location proposed by different authors since mid eighteenth centuries, based on different arguments, essentially based on: (i) distribution of damage throughout Portugal, Spain and Morocco; (ii) instrumental location of the 1969  $M7.5$  earthquake, thought to have a similar source mechanism; (iii) inverse study of the tsunami time arrival and first movement; and (iv) recent prospecting ocean floor looking for source evidences. The most recent findings consider the hypothesis of a long rupture with one or more segments. Marquês de Pombal fault might be

one of those segments, Figure 16 b). Other faults to the northern part have been identified, but neither one can explain such an enormous amount of energy that was released during the quake. A more extensive fault structure is needed to explain the approximate M8.8 earthquake.

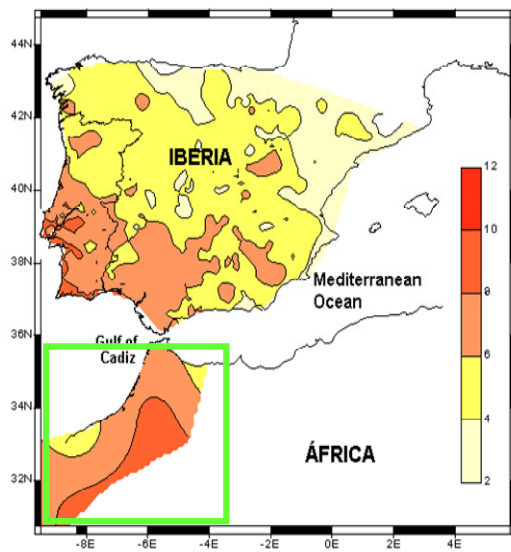


Figure 15 - MM Isosseismal map for the 1755 earthquake, in Teves-Costa *et al.* (2002)

As referred above the seismo-tectonic situation is still very far from being understood, giving rise to other hypotheses.

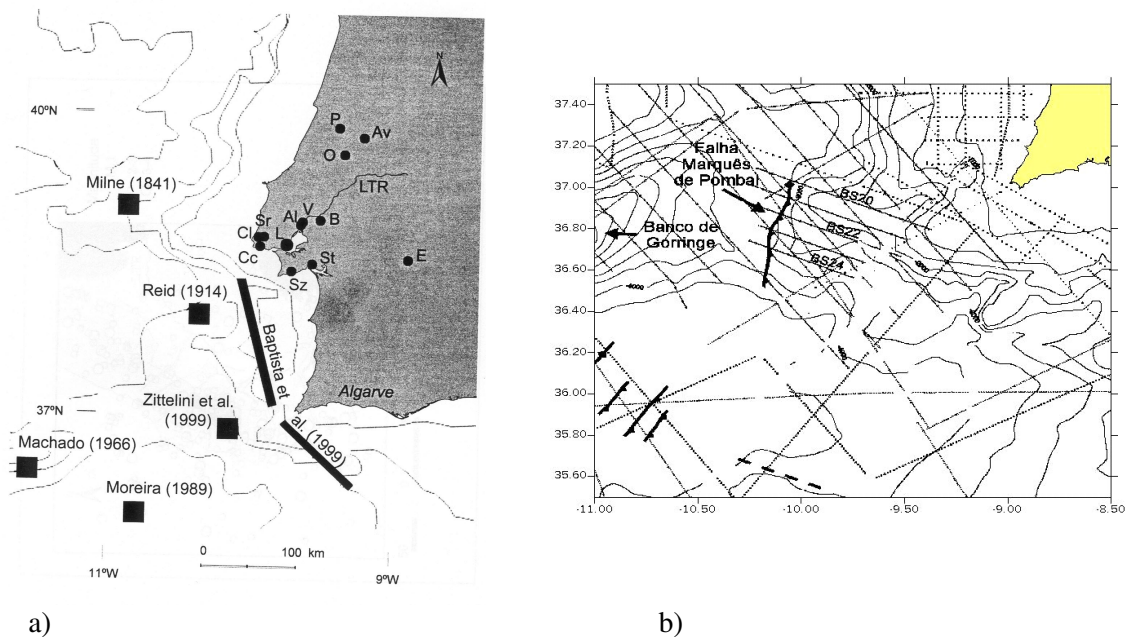


Figure 16 - Tsunami inversion: a) Localization of seismic source from arrival times and amplitudes, in Baptista *et al.*, 2001, Zittelini *et al.*, 1999, Terrinha *et al.*, 2002; b) Marques de Pombal fault

This is the case of the model proposed by Vilanova *et al.* (2004) which consider the earthquake as double trigger at far distant locations, Figure 17. This model is based on several items such as the descriptions of duration of shaking, comparison with 1969 isosseismal map and tsunami arrivals. More recent works include the existence of a subduction zone in the Gulf of Cadis as the initial cause of the 1755 earthquake.

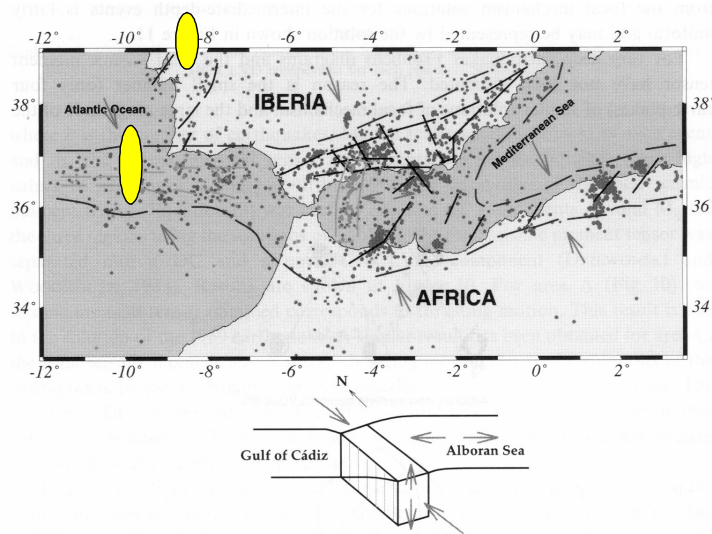


Figure 17 - Double Trigger (by sympathy) at SW Iberia and at "Lower Tagus Valley" (in Vilanova *et al.*, 2004)

Having in mind the different possibilities, Carvalho *et al.*, 2004 developed a semi-empirical rupture model for 1755 earthquake, producing the PGA values shown in the Figure 18, with values of  $400 \text{ cm/s}^2$  in the south at the nearest point to the rupture area and  $250 \text{ cm/s}^2$  in the Lisbon area. This first tentative model is in quite good agreement with the isoseismals of Figure 15.

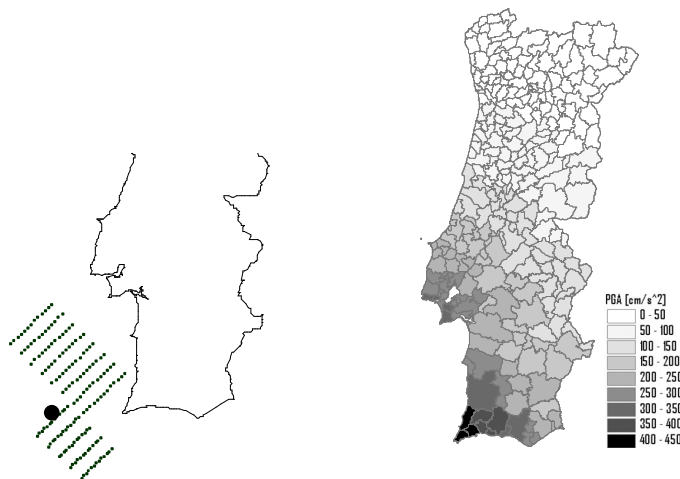


Figure 18 - PGA for a rupturing model for 1755 earthquake, in Carvalho *et al.* (2004)

A detailed analysis of this event in the southern part of Portugal, Figure 19, shows a large portion of Algarve subjected to a MM intensity VIII-IX, Pereira de Sousa (1928). In Faro, where there is an account of several damaged monuments, he attributed intensity IX. The rupturing model indicates a PGA in the order of  $250\text{-}300 \text{ cm/s}^2$ .



Figure 19 - Isosseismal map for 1755 earthquake, Pereira de Sousa (1928)

#### 4 CHARACTERIZATION OF BUILDINGS PRIOR TO REINFORCED CONCRETE TECHNOLOGY

The building stock in Portugal is characterized by a set of most varied typologies, grouped essentially into old masonry and reinforced concrete structures. Each one of these groups can be divided in several partial other groups. A detailed description of these groups can be found in (Oliveira *et al.*, 1999), where the main parameter of analysis is the epoch of construction. As an example, if we use the Census-91 (common categories for many countries in Europe) five different typologies, can be envisaged, considering the main changes in construction techniques and codes:

- T1 - Buildings constructed prior to 1919.
- T2 - Buildings constructed during the period 1919-1945.
- T3 - Buildings constructed during the period 1946-1960.
- T4 - Buildings constructed during the period 1961-1985.
- T5 - Buildings constructed during the period 1985-1991.

In the Census 2001, two other categories were added to the previous classification:

- T6 - Buildings constructed during the period 1991-1995.
- T7 - Buildings constructed during the period 1996-2001.

In many urban areas of Europe and other regions, the buildings prior to 1919 still constitutes a large portion of the existing stock, recommending a subdivision of this period into more classes. For Portugal we considered two other epochs of construction: mid-XVIII century to mid-XIX and 1850-1919. This subdivision was made in relation to past studies in zones of great predominance of ancient structures.

Masonry structures dominate until mid XX<sup>th</sup> century, and reinforced concrete suffer great evolution with the appearance of recent seismic codes. Structural quality of masonry is a decreasing function of the time since the latest earthquake event. After a catastrophic event authorities and the population are more receptive to increase the quality.

The reinforced concrete structural quality is a direct function of the seismic code evolution. The dates of 1958, 1962 and 1985 mark this evolution in Portugal. We are now in the brink of the Eurocode era with great changes with respect to structural safety of constructions.

For illustration of two important masonry typologies very common in Portugal for which we will try to determine preliminary vulnerability index, we selected the *Pombaline* buildings, built in the sequence of the 1755 earthquake, and the last phase of masonry buildings, exhibiting the worse seismic vulnerability, and built in the transition period to the reinforced concrete structures.

#### 4.1 The Pombaline buildings

After the 1755 earthquake, the new buildings erected during the first decades of reconstruction incorporated a set of features intended to provide them with adequate seismic behaviour, which means enabling them to resist horizontal loads and to dissipate substantial amounts of energy.

The "gaiola" or "cage" system consists of a set of timber members embedded along the inner face of the main stone masonry façade walls, Figure 20. These structures have been the object of several studies, indicating that, if the state of conservation of the masonries is kept, the timber members are still in "good" shape, and no removal of walls or addition of stories took place, then the overall behaviour is still ok. However, the features mentioned above are important depreciations of the overall structural vulnerability of the buildings.



Figure 20 - The "Pombaline" type – "Gaiola". Post 1755 till late XIX<sup>th</sup> century (photo by R. Langenbach)

#### 4.2 The masonry buildings - Gaioleiro (1850-1940)

This typology, which was built in the period 1850-1949, corresponding to the time of avoiding the *gaiola* to the initiation of the reinforced concrete era (RC), is very critical due to its poor vulnerability and to the large number of buildings still existing in regions of moderate to large seismic hazard.

These buildings are essentially masonry of poor quality with wooden floors and partitions. There are few elements connecting exterior walls and many are not well maintained. Figure 21 presents the view of front wall of a "good" specimen and the interior wooden framework.



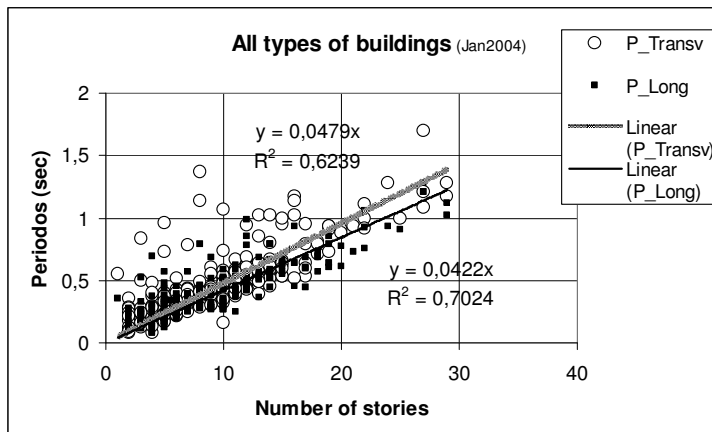
Figure 21 - The masonry buildings with wooden floors prior to 1940

#### 4.3 Initial Frequencies for different buildings

For a few vulnerability methods, among which the Hazus 99, and the one we propose (Oliveira *et al.*, 2004), the knowledge of initial frequencies (for low amplitude motion) is an essential information. This information together with source/soil predominant frequencies (through response spectra for different soil categories or free-field ambient noise) will measure the proximity of resonance and though the potential for large amplifications. Non-linear regime might change the degree of proximity and caution should be exercised in this respect.

In order to estimate the frequencies of different buildings typologies a campaign of measurements of with ambient noise has made (Oliveira 2004b) producing the results shown in Figure 22.





Types	Direction	Number	<i>a</i>	<b>R<sup>2</sup></b>
All	Trans	261	0.0479	0.624
All	Long	261	0.0422	0.702
Masonry – A	Trans	48	0.0649	0.270
“	Long	48	0.0548	0.242
RC – B	Trans	18	0.0536	0.736
“	Long	18	0.0498	0.659
RC – C	Trans	193	0.0471	0.618
“	Long	193	0.0420	0.676
“	Torsion	56	0.0320	0.352
RC - C1/C2	Trans	125	0.0480	0.652
RC - C2	Trans	20	0.0478	0.789

A, B, C1, C2 are categories of a previous study, dealing with main epochs of construction

Figure 22 - Periods of buildings under study

From Figure 22 we can see that there is a large dispersion of values denoting that other parameters beyond the number of storeys are associated to the frequency but, for the time being this information has an added value. It has been observed qualitatively in many past events that damage inflicted to buildings depends very much on the three frequency values (source-site-building) and we have a method to quantitatively incorporate them.

Several structural analysis studies have recently been performed on the *Pombaline* and other masonry structures of different types, using linear and some nonlinear analysis, isolated buildings and buildings organized in blocks (Figure 23), with *in-situ*, *shake-table* and *pseudo-dynamic* testing, but results are still very difficult to interpret and extrapolate due to the large amount of mechanical variables to characterize and some divergence in the conclusions. More examples are needed to be analyzed and tested to full collapse in order to ensure the applicability of more robust conclusions to urban areas.

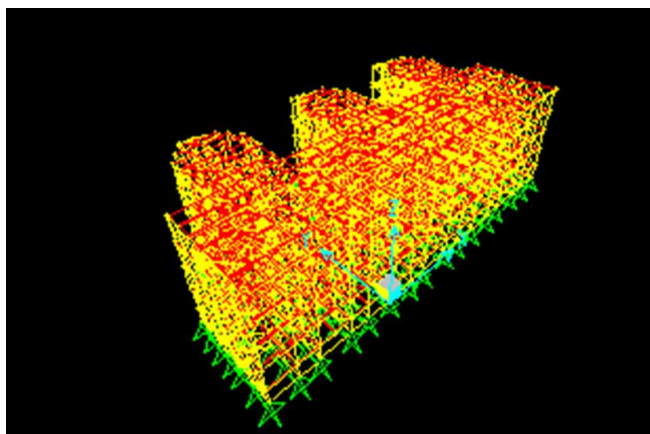


Figure 23 - Analytical modelling of a set of 3 buildings as described in Figure 21 (frequencies: longitudinal direction – 2.28 Hz; torsion – 2.91 Hz; transversal direction – 2.94 Hz)

## 5 APPLICATION CASE - FARO IN ALGARVE

### 5.1 General description and ground motion

Algarve is an important region in the South of Portugal, with 16 municipalities including Faro, its administrative and political centre.

The Algarve seismicity, as referred in section 3, results from the earthquake activity of the contact region of Euro-Asian and African plates (the West region of Cabo de São Vicente) and from the activity in the continental margin crossed by diverse local faults. Important events occurred in the past were the 1356, with intensity VIII-IX in Faro, the 1755 with intensity IX, and the 1969 Lisbon earthquake ( $M=7.5$ ) with intensity VII.

Several potential seismic sources have been proposed, but there is not yet a tectonic model of consensus among researchers, as explained in section 3. (see also Oliveira *et al.*, 2004 for more details). For this reason we selected for deterministic earthquake scenarios three historical earthquakes representing a very large magnitude distant event similar to 1755, a small/moderate magnitude nearby inland event originated at the Loulé fault and a moderate intermediate distance representing the 1964 event. Comparisons among these three situations, Figure 24, are made for the City of Faro.

Attenuation laws, influence of soils and population were used in this study similarly to the one described in Oliveira *et al.*, 2004: (i) three attenuation laws according to the proximity of seismic source; (ii) five soil classes were considered by means of predominant frequency of vibration measured by *in-situ* ambient vibration and compared with geotechnical description of soil layers; and (iii) buildings were characterised through an enquiry building by building and results compared with Census 91 for block units.

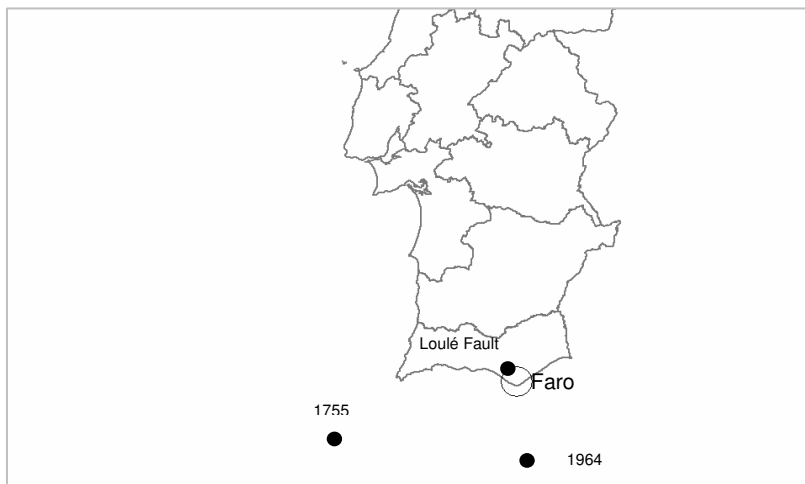


Figure 24 - Epicentral location of the earthquake scenarios

The study of the built stock of the City of Faro was initialized in 1999 (Dias *et al.* 2000) using a multi-criteria decision explained in Oliveira *et al.* (2004). In this method a detailed analysis of the various characteristics of each building was made but considers the ground motion in a simplified way, whereas the other two methods looks to the average building type by means of the EMS-98 classification and makes a more detailed ground motion analysis by considering the soil effects.

Detailing a little more the whole seismic process to define the seismic input at each location, we can add that attenuation was made in terms of Peak Ground Acceleration (PGA), but the seismic source influences the predominant frequency of ground motion vibration as a function of distance.

Soil influence was considered looking at three main descriptors. First, the regional geological setting at a scale 1:25.000; second, a local soil description, together with the determination of shear wave velocity for the most important formations; and third the estimation of predominant

frequencies through the use of the Nakamura method. These elements gave rise to five categories of soil types, classified by predominant frequencies which vary from 1 to 4 Hz.

To consider the influence of possible resonance between the incoming ground motion and the soil, we have used the simple principle of amplification given by a one degree of freedom system, having assigned a predominant frequency of ground motion as a function of distance and magnitude. A damping ratio of  $\xi=50\%$  was used.

This concept of proximity of resonance can equally be applied to the buildings, as we have a very good knowledge of different building types in terms of frequencies as referred in section 4.3. This will be the topic of further improvements of the present models. All these influences are reverted back to input PGA at the foundation of buildings, transformed into EMS-98 intensities.

## 5.2 The stock of buildings

An enormous amount of information was gathered in relation to the building stock (4334 buildings including the *Historical Centre*), which permit a good structural characterisation (between level I and II of GNDT, 1994, inquiry). Figure 25 presents the general layout of the City with buildings analysed by epoch of construction. The inquiry contains much more and detailed information that can be seen in Oliveira *et al.* (2004), such as number of stories, main structural system, structural discontinuities in height and in plan and state of conservation.



Figure 25 - Epochs of construction

All those variables were important to develop a multi-criteria model based essentially on expert opinion (Oliveira *et al.* 2004). In that study the direct objectives were: (i) to develop earthquakes damage scenarios which describe the consequences of a possible earthquake; and (ii) to prepare a risk management plan and propose an action plan for earthquake disaster mitigation.

## 5.3 Vulnerability modelling

In order to develop earthquake damage scenarios, first it is necessary to estimate the vulnerability of building types as referred in section 2.5. In this work we will use the concepts described in the EMS-98 scale (Grunthal, 1998), and implemented by Giovinazzi and Lagomarsino (2002 and 2003).

In EMS-98 some typologies are considered for masonry (M1 to M7), reinforced concrete (RC1 to RC6), steel (S) and timber buildings (W). The seismic behaviour of buildings, in terms of apparent damage, may be subdivided in six vulnerability classes, A to F (Table 1).

Table 1. Attribution of vulnerability classes to different building typologies

Type of Structure		Vulnerability Class					
		A	B	C	D	E	F
M1	MASONRY	○					
M2		○	—				
M3		○	—				
M4		○	—	○			
M5		○	—	○	—		
M6		○	—	○	—		
M7		○	—	○	—	○	
RC1	REINFORCED CONCRETE (RC)			○	—		
RC2				○	—		
RC3				○	—	○	
RC4				○	—		
RC5				○	—		
RC6				○	—	○	
S	STEEL				○	—	
W	WOOD			○	—		

○ most likely vulnerability class; — probable range,  
--- range of less probable, exceptional cases

In parallel to the typologies defined in Table 1, the EMS-98 relates intensity values with Damage grades through a qualitative description presented in Table 2. The terms "Few", "Many" and "Most" are vague and can be interpreted in different ways, as explained in the following sections. Probability Damage Matrices and Mean Damage Grade are obtained as proposed by Giovinazzi and Lagomarsino (2002, 2003) through the vulnerability index  $V_I$ . The final vulnerability  $\mu_D$  is then obtained through:

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

Table 2. EMS-98 damage description for Class A.

Damage grades	1	2	3	4	5
Intensity	V	Few			
	VI	Many	Few		
	VII		Many	Few	
	VIII			Many	Few
	IX				Many
	X				Most
	XI				
	XII				

#### 5.4 The use of Fuzzy Set Theory considering Macroseismic Scale definitions

The vulnerability classes could be well interpretable in the framework of the Fuzzy Set Theory. It is reasonable to attribute to "most probable", "probable" and "exceptional case" terms the percentage values near to 100%, 60% and 20% (Table 3). It is possible to define the membership function of each building type, as a function of the vulnerability index  $V_I$ , through a linear combination of the vulnerability class membership functions. For the membership function of each typology, five representative values  $V_I$  have been defined through a defuzzification process. Figures 26 and 27 presents an illustration of the method which has been programmed (®Excel sheet) in order to produce automatically the vulnerability index  $V_I$  result given the description of any building category in terms of its percent of classes A to F of the EMS-98 scale (Mota de Sá, 2005). The two selected typologies for membership functions were the ones referred in section 4.1 and 4.2 (*gaioleiro* and *pombalino*).

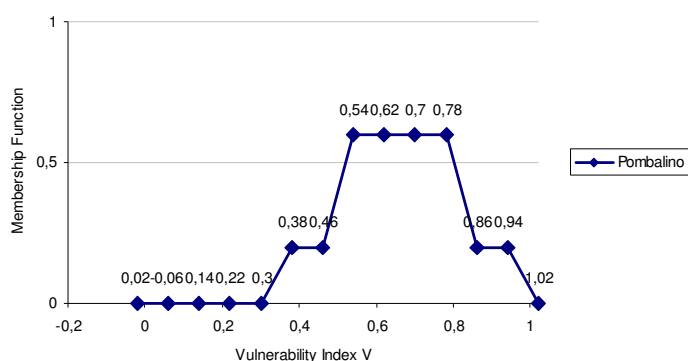


Figure 26 - Membership Function of  $V_I$  for *pombalino* typology and its representative values

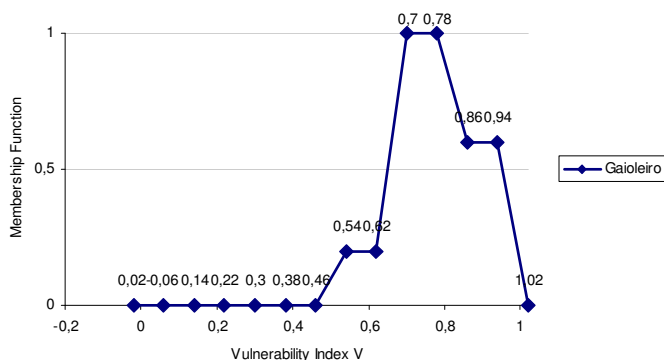


Figure 27 - Membership Function of  $V_I$  for *gaioleiro* typology and its representative values

In Table 3 we present the results for the several types of building categories using the Fuzzy Set theory, grouping the initial EMS-98 typologies into typologies leading to the same vulnerability index  $V_I$  and their upper and lower bounds.

The passage from  $\mu_D$  to damage grades characterized by 6 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).

Table 3. Meaningful values for building typologies

	A	B	C	D	E	F	V--	V-	V*	V+	V++
<b>A</b>	O						0,780	0,820	0,900	0,980	1,020
M1	O						0,780	0,820	0,900	0,980	1,020
M2	O	X					0,620	0,687	0,840	0,980	1,020
<i>Gaioleiro</i>	X	O	---				0,460	0,650	0,776	0,953	1,020
M3	---	O					0,620	0,660	0,767	0,830	1,020
<b>B</b>		O					0,620	0,660	0,740	0,820	0,860
M5	---	O	---				0,460	0,650	0,740	0,830	1,020
<i>Pombalino</i>	---	X	X	---			0,300	0,520	0,660	0,800	1,020
RC1	---	X	O	---			0,300	0,490	0,644	0,800	1,020
M4,M6		X	O	---			0,300	0,490	0,616	0,793	0,860
<b>C</b>			O				0,460	0,500	0,580	0,660	0,700
<i>Lx4060,F4660</i>		X	O	X	---		0,140	0,360	0,553	0,793	0,860
RC4		---	O	X			0,300	0,367	0,544	0,670	0,860
RC2, W		---	X	O	X		0,140	0,207	0,447	0,640	0,860
<b>D</b>				O			0,300	0,340	0,420	0,500	0,540
M7,RC5			---	O	X		0,140	0,207	0,384	0,510	0,700
RC3			---	X	O		0,140	0,180	0,349	0,480	0,700
S			---	X	O	X	-0,020	0,047	0,287	0,480	0,700
<b>E</b>					O		0,140	0,180	0,260	0,340	0,380
RC6				---	O	X	-0,020	0,047	0,224	0,350	0,540
<b>F</b>						O	-0,020	0,020	0,100	0,180	0,220

**Classes de Comportamento**

<b>O</b>	Most probable	<b>100%</b>
<b>X</b>	Probable	<b>60%</b>
<b>---</b>	Exceptional cases	<b>20%</b>

The basic vulnerability functions were adapted to the reality of Faro (Table 4). Application of penalizing functions considering the number of floors, plan and vertical irregularities, state of preservation, and other factors will be the subject of further studies. All the necessary data for this analysis is available through the GIS data-bank.

Mean damage ratio by administrative blocks of buildings, minimum and maximum values of damage, were obtained. Numbers of collapsed and seriously damaged buildings were also computed. A few of these values are presented for typical earthquake scenarios.

Table 4. Correspondence between EMS-98 typologies, Faro typologies and Vulnerability index (Giovinazzi and Lagomarsino 2002).

EMS-98 Typology	Faro Typology	Vulnerability Index
M2	Before 1900	0.840
M5	1900-1945	0.740
-	1946-1960	0.553
RC2	1961-1990	0.447
RC3	1991-2000	0.287

#### 5.4.1 Results

The results for this method are presented in Figures 27 to 29 with a summary of main values in Table 5. The selective EMS-98 intensities taking into consideration the predominance of soil frequency and of ground motion are also presented. Note that the presentation of results in geographical terms is made by block unit and not by building by building. This option was taken in order to show only the average values of what we can expect.

Table 5. Estimation of variables for different scenarios (magnitudes and epicentral distances)

Event	Magnitude	Epicentral distance (km)	Collapses	Severe Damage
1755	8.75	200	103	609
1964	7.5	50	33	31
Loulé Fault	6.5	15	10	37

As seen in Figure 28, a scenario similar to the 1755 earthquake ( $M=8.75$ ;  $R=200$  km) causes intensity IX EMS-98 in the almost entire Faro city. A total of 103 buildings could collapse and 609 become unusable buildings, with severe damage.



Figure 28 - Intensities and damage for the 1755 earthquake – distant scenario  $M=8.75$   $R=200$  km

The Figure 29 shows an intermediate scenario, located 50 km from Faro (Atlantic Ocean), with Richter magnitude 7.5. This event causes a predominance of VI EMS-98, with a maximum of X in the Historical Centre, where the soil frequencies are 4 Hz and the building stock are typically with 2 storeys.



Figure 29 - Intensities and damage for 1964 earthquake – intermediate scenario  $M=7.5$   $R=50$  km

The Loulé fault situated 15 km from Faro causes a predominance of VI EMS-98 (Figure 30). The more affected area is the Historical Centre with IX intensity. About 10 buildings could collapse and 37 exhibit severe damage.

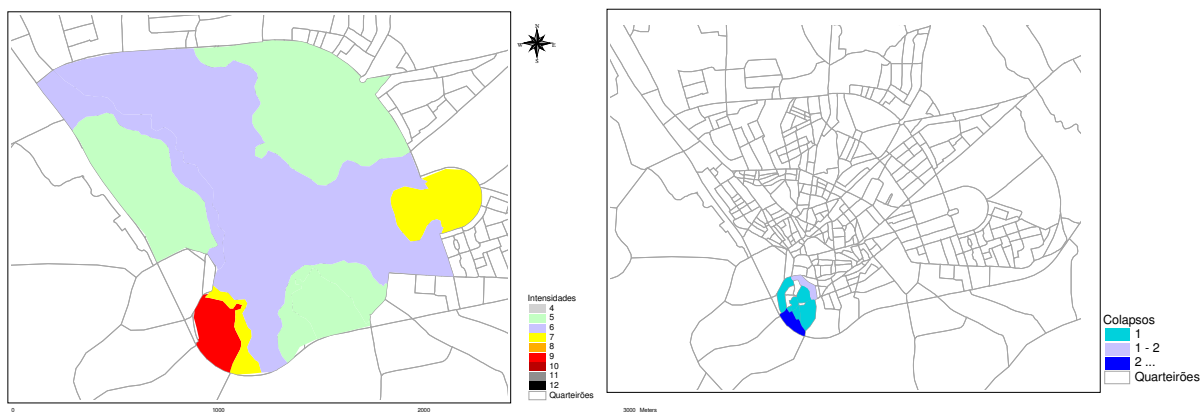


Figure 30 - Intensities and damage for the Loulé fault earthquake – nearby scenario M=6.5 R=15 km

Even though the results in terms of damage for 1964 and Loulé fault earthquakes are different (Table 5), their geographical distribution is almost identical (Figures 29 and 30) due to the same generated intensity maps. If we include in the formulation the effect of the frequency of the buildings (not yet considered), then we expect that the results would be quite different in numbers and in geographical distribution due to the selectivity in the building response.

### 5.5 The use of Macbeth algorithm considering Macroseismic Scale definitions

Another form to interpret the vagueness in the description of EMS-98 scale a new algorithm was developed. We used the same concept of EMS-98 scale and a very powerful methodology used in Multiple Criteria Decision Aid (MCDA) based on linear programming; however, it is of very friendly use and understanding. This concept was developed into the so-called Macbeth algorithm (Bana e Costa and Vansnick, 1997). Figure 30 presents an output of the Macbeth algorithm showing the levels of interdependence among different typologies and the values of vulnerability obtained.

The advantage of the Macbeth in relation to the Fuzzy theories is the clarity in the interpretation of the involved concepts, as well as the simplification of its programming. This algorithm permits to find the values  $V_1$  without using the defuzzification process, more difficult to understand.

	M1	M2	M3	M5	M4	M6	RC1	M7	RC2	RC4	RC3	w	RC5	S	RC6	Current scale		
M1	no	strong	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	extreme	0.87	extreme
M2		no	weak	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	0.82	v. strong
M3			no	moderate	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	0.80	strong
M5				no	strong	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	0.76	weak
M4					no	moderate	positive	positive	positive	positive	positive	positive	positive	positive	positive	positive	0.71	very weak
M6						no	strong	positive	positive	positive	positive	positive	positive	positive	positive	positive	0.67	no
RC1							no	weak	positive	positive	positive	positive	positive	positive	positive	positive	0.62	
M7								no	v. strong	positive	positive	positive	positive	positive	positive	positive	0.59	
RC2									no	weak	positive	positive	positive	positive	positive	positive	0.53	
RC4										no	v. strong	positive	positive	positive	positive	positive	0.50	
RC3											no	very weak	positive	positive	positive	positive	0.44	
w												no	moderate	positive	positive	positive	0.43	
RC5													no	strong	positive	positive	0.39	
S														no	strg-vstr	positive	0.34	
RC6															no	positive	0.28	

Figure 30 - Macbeth algorithm

### 5.6 The use of simple statistics considering Macroseismic Scale definitions

The third method to estimate earthquake vulnerability of the building stock using the EMS-98 concept was developed using simple statistics which consider only expected values of



vulnerability index. This method leads to the same results of the vulnerability index by the Fuzzy Set Theory, without upper and lower estimations (Table 6).

The simple statistics, not requiring the calculation of the centroid membership functions of each typology, renders the numerical algorithm easier.

Table 6. Attribution of vulnerability classes to different building typologies

	A	B	C	D	E	F
A	1					
M1	1					
M2	1	0,6				
<i>Gaioleiro</i>	0,6	1	0,2			
M3	0,2	1				
B		1				
M5	0,2	1	0,2			
<i>Pombalino</i>	0,2	0,6	0,6	0,2		
RC1	0,2	0,6	1	0,2		
M4,M6		0,6	1	0,2		
C			1			
<i>Lx4060,F4660</i>		0,6	1	0,6	0,2	
RC4		0,2	1	0,6		
RC2, W		0,2	0,6	1	0,6	
D				1		
M7,RC5			0,2	1	0,6	
RC3			0,2	0,6	1	
S			0,2	0,6	1	0,6
E					1	
RC6				0,2	1	0,6
F						1

Classes de Comportamento

O	Mais Provavel	1
X	Possivel	0,6
---	Casos excepcionais	0,2

Table 7 shows the corresponding vulnerability index values using simple statistics for all typologies used.

Table 7. Vulnerability index for the buildings typologies

	A	B	C	D	E	F	V*
A	1						0,900
M1	1						0,900
M2	0,625	0,375					0,840
<i>Gaioleiro</i>	0,3333	0,5556	0,1111				0,776
M3	0,1667	0,8333					0,767
B		1					0,740
M5	0,1429	0,7143	0,1429				0,740
<i>Pombalino</i>	0,125	0,375	0,375	0,125			0,660
RC1	0,1	0,3	0,5	0,1			0,644
M4,M6		0,3333	0,5556	0,1111			0,616
C			1				0,580
<i>Lx4060,F4660</i>		0,25	0,4167	0,25	0,0833		0,553
RC4		0,1111	0,5556	0,3333			0,544
RC2, W		0,0833	0,25	0,4167	0,25		0,447
D				1			0,420
M7,RC5			0,1111	0,5556	0,3333		0,384
RC3			0,1111	0,3333	0,5556		0,349
S			0,0833	0,25	0,4167	0,25	0,287
E					1		0,260
RC6				0,1111	0,5556	0,3333	0,224
F						1	0,100

## 5.7 Comparisons

Comparing the three approaches (Figure 31), we observe that results do not differ very much in general terms, in fact the same results were obtained with the Fuzzy Set Theory and the other simplex method using the expect value.

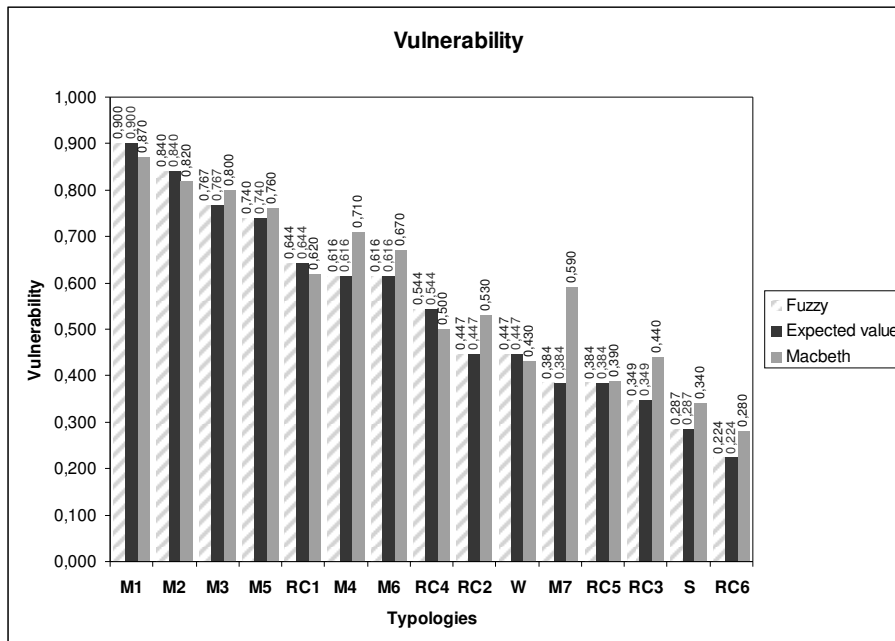


Figure 31 - Comparison of vulnerability indexes obtained different methods

## 6 FINAL CONSIDERATIONS AND FUTURE DEVELOPMENTS

There are further works in order to improve quite considerably the vulnerability and impact studies. They can be assembled into several categories:

On the earthquake process:

- The concept of spectra at the source attenuation to the firm stratum beneath each site and propagating the waves to the surface using more sophisticated models especially when the scale of interest is of great detail.
- Inclusion of more sophisticated models such as microzoning with 2 and 3D analysis and comparison with simpler 1D models.
- Selection of the earthquake scenario: historical, in agreement with a certain probability of occurrence - disaggregation (Sousa *et al.*, 2004), or taking into consideration the minimization of a given complex multi-criteria functional.

General:

- Scale of work (building; block; quarter; county; etc.)
- Inter-relations among different agencies (global versus regional or local models)
- Presentation of results (smoothing aspects)
- Probabilities associated to a certain scenario (disaggregation on magnitude and location)
- Uncertainties on estimations (methods; data; etc.)
- Quality Assessment of building inventories, updating information using, for instance, flight laser scan technology.

New Refinements on vulnerabilities:

- Vulnerabilities/Fragilities specially to account in a better way the casualty assessment
- Economical impacts
- Displacement-based design versus traditional tools (HAZUS vs ATC, EMS-98, Probability Damage Matrices, Multi-Criteria, etc.)
- Other developments in progress refer to the calibration of *capacity curves* for the different typologies. These curves, function of the initial frequency of vibration (given by the height of the building) and of the non-linear behaviour of the structural system, can be obtained in a first step by performing "pushover analysis" or other more sophisticated nonlinear analysis.

- Introduction of geometric and design concepts (soft-story; excentricities; lateral impact/support; etc.) for small scale studies.

To advance significantly in these several aspects data collected from recent earthquakes should become available and be used for calibration of models:

- On strong motion both at free-field and on the response of structures.
- On damage assessment, including human (casualties, injures and homeless) and physical, direct and indirect losses, etc.

All these refinements should be treated in the framework of GIS allowing for a continuous updating in any field of knowledge such as the new findings from recent earthquakes and research. Working at several scales enriches the knowledge and should be well articulated at all levels. This coordination of efforts is the only way to maximize the resources in case of emergency.

A final word to call the attention to the importance of understanding the level of quality control practiced in a region. The examples of the Turkey earthquake of 17 August, 1999 or the Al Hoceima, Morocco earthquake of 24 February, 2004 are extremely clear, as in many zones damage inflicted to the built stock was essentially attributed to poor quality control in code enforcement. This brings the need for, in one hand, to launch programmes for the existing structures to quantify the percentage and degree of deviation from proper enforcement of code or "good practices", and, in the other hand, to create the necessary tools (compulsive inspection, certification, insurance, etc.) to render good quality in all new construction. Using these considerations a *regional correction factor* in vulnerability curves could be included. If quality control is not considered in the analysis, the damage estimates may be completely erroneous.

These types of studies are very important at several levels for the mitigation of earthquake impact:

- Help civil authorities to define emergency plans and policies, by exercising different potential scenarios. Means and resources for emergency can be obtained from these exercises.
- Speed up the *On-line damage assessment* in case of a real event.
- Together with cost-benefit analyses at different levels, help politicians to define priorities and decide the type of need for intervention prior to earthquake occurrence. This can then be included on urban planning for future better use of the territory.

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