

# Chapter 2

## 2 State of the Art

### 2.1 Introduction

In this chapter, a review of the state of the art in seismic risk and seismic risk assessments is performed. The preliminaries contain general definitions pertaining earthquakes as the natural phenomena capable of generating catastrophic losses in urban settlements. In section 2.3, the issue on how and where different kinds of earthquakes may be generated is treated. In the following section 2.4, Seismic Risk and seismic risk assessment methods are defined and described, understanding seismic risk as the conjunction of seismic hazard and seismic vulnerability. Each of these topics is related to current researches in the world.

### 2.2 Preliminaries

Relevance of urban settlements as centers for human activities has been present through mankind history; cities are obligatory reference to whatever has to do with human beings and their activities, from inborn to death. In present days, human population in urban zones accumulates more than 70% of earth's total population. Many cities have suffered disastrous events generated by nature's power, such as: earthquakes, volcanic eruptions, tsunamis, hurricanes, landslides, floods and other that may generate destruction on human life and creations. Actually, great efforts are oriented towards the reduction of destructive effects produced by natural hazards, monopolizing attention from researchers all over the world, whose works and investigations have made possible a further comprehension and a closest look at the natural phenomena involving disasters.

At this preliminary stage is essential to define a few core concepts and relationships in order to establish a common language. Disaster is defined as “... *a serious disruption of the functioning of society, causing widespread human, material or environmental losses which exceed the ability of the affected society to cope using only its own resources.*” [ISDR, 2001]. Natural disasters are the consequence of natural hazard's impact on a socio-economic system. The process of disaster occurrence has two simultaneous (time - place) components; one is the site, with its inherent hazard, and the other is the constructed ambience over this site, including all relations and activities of urban settlements and its intrinsic susceptibility to be threatened by natural hazards. This threat degree is defined as *vulnerability*.

Coping with natural disasters has the evident consequence of the will to control these two components, unfortunately, actual state of the art in nature's comprehension and domain is

still far from allowing changes in natural forces behavior, leaving to control the component created by humanity, i.e. *vulnerability*. This determination to control undesirable natural hazards impact is defined as disaster reduction, which implies a series of strategies and “... *measures designed to avoid ... or limit ... the adverse impact of natural hazards and related environmental and technological disasters.*” [ISDR, 2001]. Avoiding implies taking measures in order to eliminate the possibility of disasters; this strategy is best known as *prevention*, i.e. awareness of natural hazards and the consequent restrictions for hazardous sites. Limiting, comprises both control of the built environment (through seismic performance improvement) defined as *mitigation*, and the effective response of institutions and population to the impact of natural hazards, defined as *preparedness*.

The essence of this research is oriented towards assessing natural hazards that may develop in natural disasters, particularly earthquakes, and the consequences inflicted upon urban environment and its population (i.e. losses due to damage and collapse of the built environment and casualties and injured produced in this degradation process). In case of earthquakes (as in all natural disasters) it is impossible to reduce nature’s destructive power; experience has shown that the cornerstone for impact reduction relies on preparing urban settlements and population to withstand certain expected seismic events, attempting to reduce damage and consequent losses. This means to comply for earthquake prevention, mitigation and preparedness in an urban settlement.

General procedure for earthquake disaster reduction consists in the assessment of the interest zone, taking account for specific topics that characterize the dynamic behavior of the soil and the built structures when exposed to a certain seismic event. These behaviors and their possible effects must be measured by some parameter, usually economic, that indicates in some way the amount of losses and consequently the strategies and priorities to follow after an impact. Assessment is then data acquisition and treatment; the nature of this process is multi-sectorial and interdisciplinary involving a wide variety of interrelated activities at local, national, regional and international level. Results of assessments are integrated into reports that establish the principal strategies and actions for planning (prevention, preparedness) and constitute the basis of seismic building codes for the zone (mitigation). The experimental base that supplies fundamental information used in developing general and specific strategies has to be in permanent evaluation and updating, as new methodologies and researches feed the problem’s possible solutions. Although having state of the art seismic codes, reliability percentages, though acceptable, are never 100% and only the occurrence of a seismic event can realistically test the codes and establish parameters to evaluate its assertiveness.

Recent earthquakes (Loma Prieta in USA, Kobe in Japan, and Mexico D.F. in Mexico) have proved that reliability in codes is limited, because unexpected local-site phenomena can occur and cause great damage. Then, all the possible analysis must be performed exhaustively including all possible local effects i.e. closing the analysis resolution in the interest sites so to acquire reliable data. For this reason, it is mandatory to improve post-earthquake evaluation, considering all the possible factors involved, with a holistic focus on the problem, also being essential an interdisciplinary interaction in the process.

Even though difficult in practice (because of uncertainties in seismic knowledge still exist) great attempts have and are being oriented towards an improvement not only of structural dynamic performance of built environment but also in its physical layout inside urban space available. Therefore, although structures gain capability to withstand certain seismic events, their location in the urban area must also be the best possible, avoiding at all means soils with high local amplifications and/or contour related problems (steep slopes, with high probabilities of landsliding).

As in any planning procedure, the problem should be analyzed in several scales or resolutions. To this moment, only cities have been mentioned, though other spaces exist, such as the interurban one, which comprises spaces for communication, and conduction between cities. It is important to know that cities are not isolated. They are interdependent in a territory; urban centers tend to specialize based in its economic, strategic (geographic) and social characteristics, configuring a unique physic morphology linked to the surrounding territory. Territorial configuration is more like a web composed by a group of cities that interact and where each of them has a specific role in the context. Therefore, seismic risk assessments must attend all the possible contexts, local, national, and regional, attempting to establish the leading lines for planning and decision-making strategies.

Actually, a widely extended methodology used in seismic phenomena research and its impact on urban areas is being carried out through the generation of seismic risk scenarios for a specific location. The most important factors involved in seismic events can be identified based in data acquisition for both soil and buildings structural dynamic behavior undergoing a particular seismic input (characterized by the seismicity of the zone). Fundamental and complex problems are encountered in this procedure, not only to identify the behavior of soil and structures, but also the seismic input. In [Bertero, 1992], these complexities are thoroughly explained identifying two major problems in the definition of the case (Figure 2.1). The first is the accurate estimation of ground motion in the foundation of the building ( $X_3$ ), depending on prediction of power and recurrence in seismic source, with the respective attenuation law so to evaluate changes in seismic waves from the focus to the rock basement of the site ( $X_1$ ); and the surface site response characteristics ( $X_2$ ). The second, prediction of the deformation, for a particular building ( $X_4$ ) in response to a specific ground motion ( $X_3$ ) which depends on the combined effect of the dynamic characteristics of main excitations acting on the building, such as: “...(1) gravity forces,  $G(t)$ , with the associated effects of volumetric changes produced by creep of the structural material, specially concrete, (2) changes in environmental conditions,  $E(t)$ , such as stresses produced by variations in temperatures, humidity, wind and snow; and (3) at least three translational components of the foundation shaking,  $X_3(t)$ .”.

The objective of seismic risk assessment is to evaluate, as accurately as possible, the malign effects of certain earthquakes on the built environment and its consequences. This means the *damage* generated on civil structures, understanding damage as the physical degradation process that undergoes a structure when subjected to a certain seismic input; and the possible casualties or injuries suffered by the inhabitants. Damage is the key to comprehend the real impact, nevertheless, it is not a simple task, which requires special modeling (numerical and experimental) for an accurate prediction of behavior of soils and buildings, these models are not still available at the required level [Bertero, 1992; Meli and Alcocer, 2000; Holmes, 2000]. Actually, modeling of structures is limited to the frame, i.e. structural elements that compose the civil work; analyses of the whole, including all non-structural elements are carried through empirical formulae available from previously observed damage patterns in constructions. In the design process, simplifications of the input and linearization of the response are most of the times applied, due to the lack of accurate data for seismicity and the high cost that implies non-linear detailed modeling of structures. Only special facilities with strategic relevance i.e. dams, nuclear power plants, military strategic facilities, are designed exhaustively applying all the possible tools available.

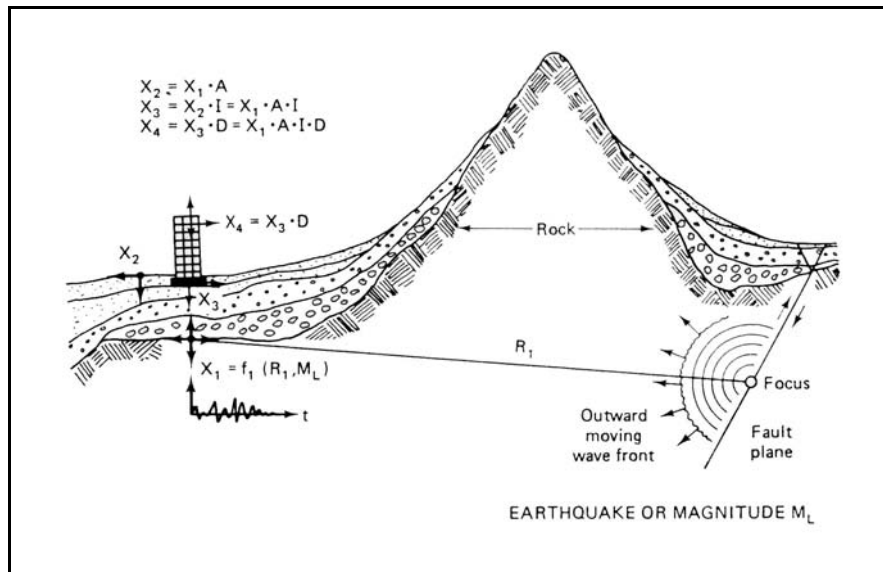


Figure 2.1: Problems and factors involved in predicting the seismic response of a building. [Bertero, 1992].

Models for earth crust and soil behavior are empirical in most cases. Generally, models are obtained from shock evaluations by means of seismic instrumentation or by geophysical surveys, releasing a series of data that describe (to a certain level of reliability) the dynamic behavior of soils and sub-soils. Many uncertainties still govern the behavior of earth crust and soils, being dramatic in places where surveys and instrumentation are not available and/or seismic codes are weak and not adequate to the real context.

### 2.3 Plate Tectonics as Seismic Event Sources.

Earthquakes (seismic events) may be defined as “...chaotic movements of earth crust characterized by a time-dependency of amplitudes and frequencies...” [Barbat and Canet, 1994]. Foci for these events occur anywhere from the surface to about 700 km in depth; however, 75% of these have depths shallower than 60 km and are called shallow-focus earthquakes [Coch, 1995].

Earthquake generation may be classified, depending on the nature of the source, in four general types [Scheidegger, 1975]:

- Tectonic earthquakes: caused by rock rupturing in response to tectonic stresses at active plate margins, where one moving plate overrides another, grinds longitudinally through the plate margin with another or converges with another, defining a fault. These earthquakes constitute the strongest and the most frequent.
- Volcanic earthquakes: volcanic eruptions associate seismic events, not only because of the same tectonic origin for both, but also due to gas explosions during eruption. Generally produces small intensity movements over limited surfaces.
- Collapse earthquakes: originated by subterranean cavity collapse and characterized by a low intensity.
- Explosion earthquakes (human-made): are seismic events produced by the testing of massive destroy weapons (such as nuclear weapons) carried in subsoil depths (for contamination control). In most cases are capable of generating telluric movements of such magnitudes that are felt in the surface.

Reviewing the classification, and based on catastrophic experiences throughout the world it may be stated that the most powerful and frequent earthquakes are those generated by tectonic phenomena “... over 90% of earthquakes occur where tectonic plates move against one another in some manner...” [Coch, 1995].

Plate tectonics is a relatively recent theory, its origins can be found in the first decades of the 20<sup>th</sup> century with Alfred Wegener’s proposal of the “Continental Drift Theory” in 1912. Based on paleontologic, stratigraphic and geophysical researches, concluded that in the Paleozoic Era existed a unique continent called, by him, Pangea. This super-continent assembled all continental masses existing nowadays. Between the Cretaceous and Quaternary Eras, Pangea fractured forming the continents that we know today, which separated and derived to its actual positions.

This theory was not accepted in its moment because of the lack of evidence and the unawareness of the mechanisms capable of moving continents over the presumed solid or plastic subsoil. It wasn’t but until the mid-20<sup>th</sup> century (after World War II), with the development of paleomagnetism and submarine geophysical explorations, that this theory was scientifically verified. With paleomagnetism (recognition of remnant magnetism in rocks), it was found a different magnetic orientation of that it should be. Submarine geophysical explorations allowed discovering sub-oceanic mountain chains with temperature flow higher than the rest of the ocean floor, and long narrow deep depressions (trenches), both coinciding with high seismicity zones of earth. The following may summarize capital results of researches in oceanic floor exploration:

1. Oceanic mountain chains are characterized by a temperature flow greater than in the rest of the ocean floor, and determine locations with high frequency of earthquakes.
2. The Pacific Ocean border from Chile to Alaska and from there to New Zealand, also the Malaysian Archipelago and other zones such as the Caribbean Sea are characterized by the presence of long narrow and deep depressions denominated marine trenches. These coincide with narrow stripes where the greatest number of earthquakes on earth surface occurs.
3. The rest of the ocean floor is practically inactive with a low frequency of earthquakes.

Based on these and other conclusions, Harry Hess and Robert Dietz proposed independently, in 1961, a theory that explains how oceanic floor forms in rift valleys. In these locations, basalt is extruding to form new oceanic crust moving apart blocks of the lithosphere. General conclusion is that the permanent generation of oceanic crust pushes tectonic plates and consequently induces movement [Schubert, 1984]. Plate Tectonics Theory establishes that in rift valleys large slabs of the lithosphere are created and separated from each other with an almost perpendicular oriented movement respect the rifts. This movement as well as the continual generation of oceanic crust are permanent and explain the seismic activity and movements verified along plate boundaries.

Plate movements, as explained above, are the source for the majority of seismic events in the world, and they depend on how tectonic plates move and interact with each other. The contact surfaces between plates are defined as faults. Earthquake generation is located inside faults, where stresses build up over some parts of this area (barriers, asperities) until reaching the maximum capacity of crust materials. At this stage, instant energy liberation is produced through fracture generating strain-release i.e. instantaneous movements in the fault.

Faults may interact in three different fashions, consequently generating different types of earthquakes:

- Compressional faults: also defined as convergent faults, the contact surface is stressed through compression due to plates moving one under the other, lifting a portion of the

upper plate. This movement is called *subduction*; it may generate shallow or deep earthquakes with great power, having exceeded magnitude 9.0 Richter in Alaska (March 28<sup>th</sup> 1964) and in Chile (May 22<sup>nd</sup> 1964) subduction zones.

- Extensional faults: also called divergent, stresses are extensional, separating tectonic blocks and producing downward movements through sloping fault plane in one of the blocks, sinking relatively to the other. Earthquakes are shallow and aligned over the spreading axis, with low magnitudes.
- Transform faults: also defined as strike-slip faults, plates mostly slide past each other laterally (strike-slip movement), producing less sinking or lifting of the ground than extensional or compressional faults. Earthquakes are usually shallow and their magnitude strongly depends on the local tectonics in the area being possible great extensional earthquakes when the fault changes in direction, as the San Andreas Fault and the faulting system in Sumatra, which recently generated a very strong earthquake (estimated as a Moment Magnitude 9 earthquake) [EERI, 2005].

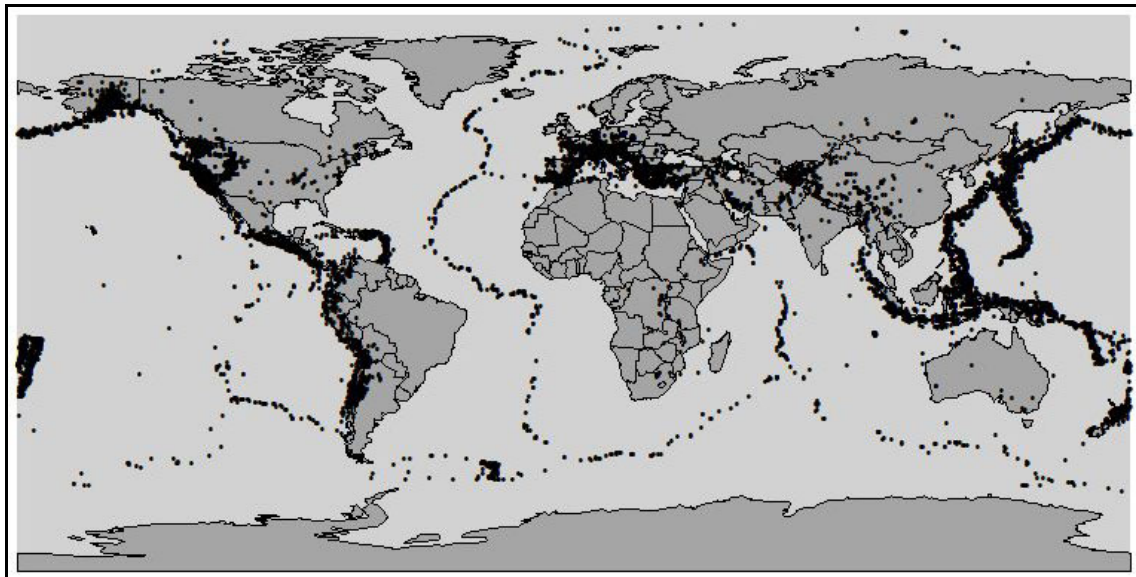


Figure 2.2: World Seismicity Map 1998-2000 (Data downloaded from: <http://spatialnews.geocomm.com/features/quakes2000> ).

In a world seismicity map (Figure 2.2), seismic activity reveals the trace of faults in earth's crust, coinciding with continental mountain ranges, oceanic trenches and ridges; places where lithospheric blocks are in contact. Seismicity belts around the world comprise hot lines of activity over earth's crust, dramatically coinciding with populated portions of the continents.

## 2.4 Seismic Risk

Seismic Risk is understood as the expected losses in an *element at risk* during a specific time interval due to the occurrence of a determined seismic event. An *element at risk* may define: a single construction or group of these, an urban zone, an entire city or the people that live in it. In addition, economic activities, public services or communication lines (utilities and lifelines) should be also considered as elements at risk. Thus, risk may be measured by means of casualties, economical losses, social impact or physical damage of constructions, depending on which definition of element at risk has been considered.

Seismic risk evaluation represents a complex problem, where seismicity contributes as the source of movements affecting elements at risk. Assessing seismogenic sources through

monitoring, may establish approaches to energy liberation recurrence and power so to understand and generate behavior patterns of events in time. These assessment results are defined as the *seismic hazard* for the zone, one of the two components of seismic risk. This variable is not controllable by man though great efforts have and are being oriented towards a reliable comprehension of patterns for energy liberation in faults and wave propagation through earth's lithosphere-asthenosphere system.

Elements at risk constitute the other component of seismic risk, as *damage* generated by seismic events affects their physical integrity and functionality. Damage and its classifications are clue concepts in this context, revealing the physical degradation of an element at risk and its consequences. A parameter used in measuring this probable degradation is *seismic vulnerability*, which represents the intrinsic sensibility of an element at risk to be damaged by a certain seismic event.

Understanding seismic risk as a confluence of independent parameters, with seismic hazard at one side and seismic vulnerability on the other, helps to explain the actual risk status in earthquake prone areas in the world. Hazard, as a natural feature of the zone cannot be changed, but can be reliably identified so to control occupation on the area or at least to establish an awareness of the hazard. Vulnerability, on the contrary, may be controlled and seismic performance of elements at risk may be improved. Although a possible solution, improvement is not a straightforward or simple task, taking into account the great quantity of elements that may not fulfill an adequate performance, or are/were built not considering code recommendations. In addition, the development due to economic and societal dynamics generates growth in the cities (in population and area), enlarging consequently the number of elements at risk and defining new ones. Thus, even as seismic risk assessment serves for prevention, preparedness and mitigation, tending to cover all possible scenarios, permanent changes in constructed environments and activities generated by dynamics in economy and society, produces a growth on seismic risk at the same pace of development [Meli and Alcocer, 2000].

Throughout this research, seismic risk will be focused on buildings as the primary problem inside an urban location, because building collapse and space damage are the principal reasons of casualties, injured and general losses in case of earthquakes. So, when referred to seismic vulnerability, the context must be understood as the buildings existing in the urban environment and their performance under seismic events.

### 2.4.1 Quantifying Seismic Risk

As seismic risk depends on seismic hazard and seismic vulnerability, its quantification implies a previous assessment for these two variables, which will be explained in detail forwardly in this chapter.

As a quantified parameter, seismic risk is referred to damage and the cost implied in the degradation process. An useful mathematical interpretation for this analysis is given by [Sandi, 1983]; formulae describes a *Specific Seismic Risk (S)*, which represents the probability of a structure or group of these to suffer one or several damage grades in a given time interval (defined as exposure time) in a specific hazardous zone. For this purpose, it is essential to identify the *Seismic Hazard* for the zone and the *Seismic Vulnerability* of the built environment. Specific Seismic Risk is the result of the convolution ( $\otimes$ ) between Seismic Hazard (**H**) and Seismic Vulnerability (**V**), both expressed as probabilities. Seismic Risk (**R**) is the result of convolution between Specific Seismic Risk (**S**) and the Cost (**C**) of the elements at risk, identifying the expenses required for repairs or reposition after the possible earthquake impact; equations are:

$$S = H \otimes V \quad \text{eq. 2.1}$$

$$R = S \otimes C \quad \text{eq. 2.2}$$

This quantification approach to seismic risk, although not unique, represent a consensus in the present, general practice agrees in applying this formulation to assess seismic risk [Bertero, 1992; Holmes, 2000; Zonno et. al., 1998; Belloni et. al., 1998, Mèneroud et. al. 2000; Pujades et. al. 2000; Nikolaev et. al., 1998; Giovinazzi and Lagomarsino, 2004; Multinovic and Trendafiloski; Vacareanu et. al., 2004], which also serves as basis for insurance policy cost estimations.

The final objective of risk assessment is then an estimate cost of losses related to physical degradation of buildings and the possible consequences to the inhabitants. Results, although useful for planning strategies and insurance policy estimations, are however, not complete in the sense of including all possible effects on urban environment. General practice leads to partial estimations of real consequences, this means that other cost analyses such as the overall economic and societal costs are not taken into consideration, Mujumdar (2000) explains: *“In the current socio-economic environment ... overall risk assessment must extend to business interruptions, economic losses, disruption of social systems and long term effects on the community.”* Once more, holistic approach to assessment problem must be performed, this time with a great handicap: economic and societal risks lack of agreed quantification procedures and the data required is still unavailable at the level required. Actual trends and new paradigms in general strategies for seismic risk assessment will be exposed forwardly in this chapter.

## 2.4.2 Seismic Hazard

Seismic Hazard may be defined as the probable occurrence, within a specific period of time and in a limited zone, of a seismic event with certain characteristics. It implies measure of the power for an expected earthquake and for a particular site, depending on the features of a certain seismogenic source. Seismic hazard analysis results may be defined as predictions, containing the probable occurrence for different earthquake sizes at a specific site. Parameterization for the assessment process implies representations of earthquake source, wave propagation path and site response. Each one of these representations has different definitions and interpretations depending on the approach used for assessment. Two different approaches are available in the general methodology: a deterministic and a probabilistic approach.

### 2.4.2.1 Deterministic Seismic Hazard

Identifies the maximum possible event from past earthquakes, considering future seismicity in a region similar to the past, providing a scenario earthquake for the evaluation of the worst-case ground motions.

General procedure for Deterministic Seismic Hazard Analyses (DSHA) identifies and delimits seismogenic sources that may impact a site, with the corresponding historical maximum events (seismic zone potential); attenuation laws are used forwardly to estimate ground motion parameters (mainly intensity and acceleration but also spectral values) and a site categorization serves to the purpose of evaluating site effects. Ground motion models used to perform predictions are simplified and most of the time empirical in parameterization; e.g. *“... the effects of the earthquake source is represented by earthquake magnitude; the effects of wave propagation from the earthquake zone to the region are specified by a distance; and the effects of the site are specified by a site category.”* [Somerville, 2000]. Finally, results are



presented in the form of a unique parameter that describes the maximum ground motion at the site. It may be inferred through different methods, such as:

- Seismic catalogs: the collections of recorded events, instrumental or historical, serve as a basis for the assumption of the maximum possible event. The most important problems in this approach are: the period enclosing the catalog in most of the cases only a few hundred years, and the quality of the catalog. In low seismicity areas, quantity and quality of data available usually does not allow the reliability desired in the decision of choosing an event.
- Tectonics: maximum earthquake definition is based in fault displacement measures per year, and its comparison with the total displacement occurred in the most important earthquakes. This is performed through the measurement of the rupture produced in an historical earthquake (by means of paleogeology and geology assessments) and the cumulative displacement per year of the fault (or faults), supposing that Strain-release will be the same in the future.

The most important feature in DSHA is the subjectivity in decisions that involve the evaluation of the seismic zone potential, requiring the expertise and opinions of several different professionals (seismologists, seismic geologists, engineers, risk analysts, economists, social scientists and governmental officials). This might cause difficulty in reaching a consensus on earthquake potential, due to the different backgrounds and goals of such professionals [Kramer, 1996].

The chosen event scenario describes the worst case of ground motion, but does not describe the likelihood of occurrence of this event. Therefore, a lack of information exists on how often it is likely to occur, the level of ground motion expected during a finite period of time (e.g. lifetime of constructions or facilities) and the uncertainties introduced in the process required to estimate the resulting ground motion characteristics.

#### 2.4.2.2 Probabilistic Seismic Hazard

One of the most powerful tools for earthquake prediction is assessment through probabilistic analyses, where seismic events are considered as stochastic (i.e. non-deterministic) events. Some probabilistic models may describe, to a certain level of reliability, the behavior in time and space for seismic events generation in a delimited zone, and forwardly estimating effects by means of attenuation laws. Prediction in this case points towards estimating the recurrence of events through probability of occurrence and return periods for these events. The problem is not simple as many variables and parameters are involved in the process, requiring an extended set of data, in this case: observational data. The latter represents the core of the problem: the data available must be extensive in time and reliable by means of data collection quality and treatment. Earthquake generation process is approached through time and space probabilistic models, based in observed seismic behavior.

Time modeling is usually based on Poisson's model, which considers that an earthquake may occur at any time. The number of occurrences in a short time interval  $\Delta t$  is independent of occurrences in some other time interval, as long as the two do not overlap; and, the occurrence probability for an earthquake is  $v\Delta t$ , where  $v$  is the occurrence ratio, taken to be constant and the occurrence probability for more than one earthquake in  $\Delta t$  is negligible. The probability that in a finite time interval  $t$ ,  $n$  earthquakes may be generated is:

$$P_t(N = n) = \frac{(v t)^n}{n!} e^{-v t} \quad \text{eq. 2.3}$$

Probability distribution in a time interval  $T$  between two consecutive earthquakes is:

$$F_T(t) = P(T \leq t) = 1 - e^{-\nu t} \quad \text{eq. 2.4}$$

The most important highlight in this probabilistic model is that the occurrence of an event is affected neither by past nor by future event occurrences, this is known as memory absence in Poissonian processes. The model is very simple, direct and useful in general seismic hazard analyses, not considering premonitory events, replicas or seismic swarms. Other time models are available, such as Non-homogeneous Poisson, Bayesian and Markov chains, which consider memory in the process of time occurrence, hence needing a very complete seismic catalog and complicated procedures to be performed.

Space models identify and locate seismogenic sources for earthquake generation (supposing time and space occurrences as homogeneous inside the source) describing behavior through frequency-magnitude relationships. Sources may be identified depending on characteristics taken in consideration at the time of analysis; generally, four types of seismic zones are used:

- Seismo-tectonic zones: establishes relationships between earthquakes and geologic structures (faults).
- Paleoseismic zones: without recent seismic history, paleoseismicity in Holocene period (approximately the past 10,000 years) may suppose a future seismicity as the fault may be defined as an active one. For example, the California Division of Mines and Geology defines an active fault as one that has produced surface displacement within Holocene time.
- Seismogenic zones: relationships between geologic structures (faults) and earthquakes is not very clear; although grouping of events may be inferred as associated with a particular fault, no evidence of Holocenic seismic activity indicates active faults.
- Seismicity zones: are defined only for the purpose of seismicity distribution in time, not considering relationships with geologic structures, delimitations in space are focused exclusively for general seismic hazard estimation.

Generally, two probabilistic approaches may be differentiated depending on considerations for seismogenic sources: zoned and non-zoned probabilistic analyses.

a) Zoned probabilistic analysis:

Also defined as Probabilistic Seismic Hazard Analysis (PSHA), identifies and locates the seismogenic sources that may impact the site, supposing that seismicity is homogeneously distributed over the sources. Modeling includes time of occurrence and distance from the source using for this purpose attenuation laws, i.e. not only occurrence in time, but also space distribution of events is analyzed [Peláez, 2000]. Mathematically, this approach is based in the *total probability theorem*, stating a probability of exceedance for a certain value  $y$  of a parameter  $\zeta$  of a ground movement by the following equation:

$$P(\zeta > y) = \int_{\tilde{x}} P(\zeta > y | \tilde{x}) f_{\tilde{x}}(\tilde{x}) d\tilde{x} \quad \text{eq. 2.5}$$

Where  $\tilde{x}$  includes all random variables involved in the result (usually magnitude and distance are chosen) and the multiple integral must be calculated over all variables in it,  $f$  being their probability density functions and  $P(\zeta > y | \tilde{x})$  being the conditional probability to exceed a value  $y$  given a determined value for the involved variables  $\tilde{x}$ . Supposing  $n$  independent seismogenic sources identified and located, with an  $\nu_i$  occurrence rate for each one, the latter equation takes the form of a weighted average:

$$P(\zeta > y) = \sum_{i=1}^n \frac{\nu_i}{\nu_{\tilde{x}}} \int P(\zeta > y | \tilde{x}) f_{\tilde{x}}(\tilde{x}) d\tilde{x} \quad \text{eq. 2.6}$$

Where the sum is extended to all potential hazard generation zones and  $\nu$  is the total region occurrence rate, i.e.

$$\sum_{i=1}^n \nu_i = \nu \quad \text{eq. 2.7}$$

If random variables as magnitude ( $m$ ) and distance ( $r$ ) are used, the equation for total probability (2.6) will be:

$$P(\zeta > y) = \sum_{i=1}^n \frac{\nu_i}{\nu} \iint_{R,M} P(\zeta > y | m, r) f_m(m) f_r(r) dm dr \quad \text{eq. 2.8}$$

b) Non-zoned probabilistic analysis:

Performed over a seismicity zone, it is usually delimited as a rectangle or circle of a certain size, which contains seismic activity that may affect the interest site. The seismogenic sources are not considered. This approach is commonly used for general seismic hazard analyses, i.e. time distribution of events. It is based in the application of different models; being the most widely used the Extreme Value Distributions. The method is based in maximum values distribution for a given variable (Macroseismic Intensity, Magnitude), in certain time intervals for the interest zone, which normally are more homogeneous and precise in time than other type of data. For this research, the most used distributions are the Gumbel extreme value models (types I, II and III). All of them are based in the same principles: random variable  $y$  is the maximum for a series of  $n$  independent random variables  $x_i$ ; where  $x_i$  is the maximum for a series of values representing a parameter of ground motion (Intensity, Acceleration, Magnitude) in a certain zone for constant time intervals. Differences between the three Gumbel distributions depend on the proposed limits; Gumbel I, considered unlimited, because of the absence of upper and lower limits, has the general form:

$$F(y) = P(\zeta < y) = e^{-e^{-\alpha(y-u)}} \quad \text{for, } -\infty < y < \infty \quad \text{eq. 2.9}$$

Where  $u$  is the most frequent value of the distribution and  $\alpha$  is a measure of the dispersion of the extreme values; these parameters are given by the following expressions:

$$\alpha = \frac{\pi}{\sqrt{6} \sigma_x} \quad \text{eq. 2.10}$$

Where  $\sigma_x$  is the standard deviation of the data, and

$$u = \bar{x} - \frac{\gamma}{\alpha} \quad \text{eq. 2.11}$$

Where  $\gamma = \text{Euler's Constant}$  (0.5772156649...) and  $\bar{x}$  is the average value of the  $x_i$ .

Gumbel II distribution considers a lower limit, with distribution function:

$$F_Y(y) = \exp \left[ - \left( \frac{u - \varepsilon}{y - \varepsilon} \right)^k \right] \quad \text{for, } u \leq y \leq \infty \quad \text{eq. 2.12}$$

Where,  $\varepsilon$  is the lower limit imposed to the independent variable  $x_i$ ;  $u$  is the value in which the function falls to  $1/e$ , and  $k$  is a shape factor, which helps to fit the function to the data curve analyzed.

Gumbel III establishes two imposed limits, having the form:

$$F_Y(y) = \exp\left[-\left(\frac{\omega - y}{\omega - u}\right)^k\right] \quad \text{for, } u \leq y \leq \omega \quad \text{eq. 2.13}$$

Where,  $u$  is the lower and  $\omega$  the upper limit for the values in the distribution.

General procedure for analysis considers the maximum felt events ( $x_i, i=1, \dots, n$ ) for a specified location in constant time intervals  $\tau$  and through the seismic history considered ( $n\tau$ ). Forwardly, maximum events are ordered increasingly as distribution values for prediction, using the different expressions for the different Gumbel Distribution Types:

$$\text{Type I: } F_{x_i} = \frac{i}{n+1}, \quad [\text{UNESCO, 1980}] \quad \text{eq. 2.14}$$

$$\text{Types II and III: } F_{x_i} = \frac{i - 0.44}{n + 0.12}, \quad [\text{Peláez, 2000}] \quad \text{eq. 2.15}$$

Performing different fits for distributions, parameter values are calculated, and the probability of exceedance for a certain event  $y$  (measured by means of the chosen ground movement parameter) in a time interval  $t$  will be:

$$P(\zeta > y) = 1 - F_Y(y)^{\frac{t}{\tau}} \quad \text{eq. 2.16}$$

With a return period for ground movement:

$$PR(y) = \frac{\tau}{P(\zeta > y)} = \frac{\tau}{1 - F_Y(y)^{\frac{t}{\tau}}} \quad \text{eq. 2.17}$$

Comparison for these distribution types is performed using a seismic catalog for Mérida city collected in several research reports [MOP, 1976; FUNDAPRIS, 2000; NEIC, 2001] between years 1950 and 1999. This catalog is shown in Figure 2.3. Forty-nine years is the period of study ( $n\tau$ ), where maximum events (in magnitude) are chosen as the highest one in a year ( $n = 49, \tau = 1$  year). The minimum magnitude for events is 4.5 and the maximum is 7.0 in a seismicity zone corresponding to northwestern Venezuela, between UTM coordinates W  $68^\circ$  to  $74^\circ$  and N  $6^\circ$  to  $13^\circ$ . Using the distribution values in (eq. 2.14) and (eq. 2.15) for the corresponding increasing magnitudes array (between magnitudes 4.5 and 7.0), a sample data distribution is built. Statistic parameters are estimated for the magnitude distribution, where the most frequent value in the sample data is  $u = 5.32$  and the Standard Deviation is  $\sigma_x = 0.55$ . Fits to the curve are performed over the distribution samples of  $F_{x_i}$  using the expressions for the different Gumbel distributions. For Gumbel II and III distributions, shape factor variation is used to obtain the best correlation between the curve and the data; the correlation factor used has the form:

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x \cdot \sigma_y} \quad \text{eq. 2.18}$$

Where,  $\sigma_x$  and  $\sigma_y$  are the Standard Deviation for variables  $x$  and  $y$ , and

$$Cov(X,Y) = \frac{1}{n} \sum_{i=1}^n (x_i - \mu_x)(y_i - \mu_y) \quad \text{eq. 2.19}$$

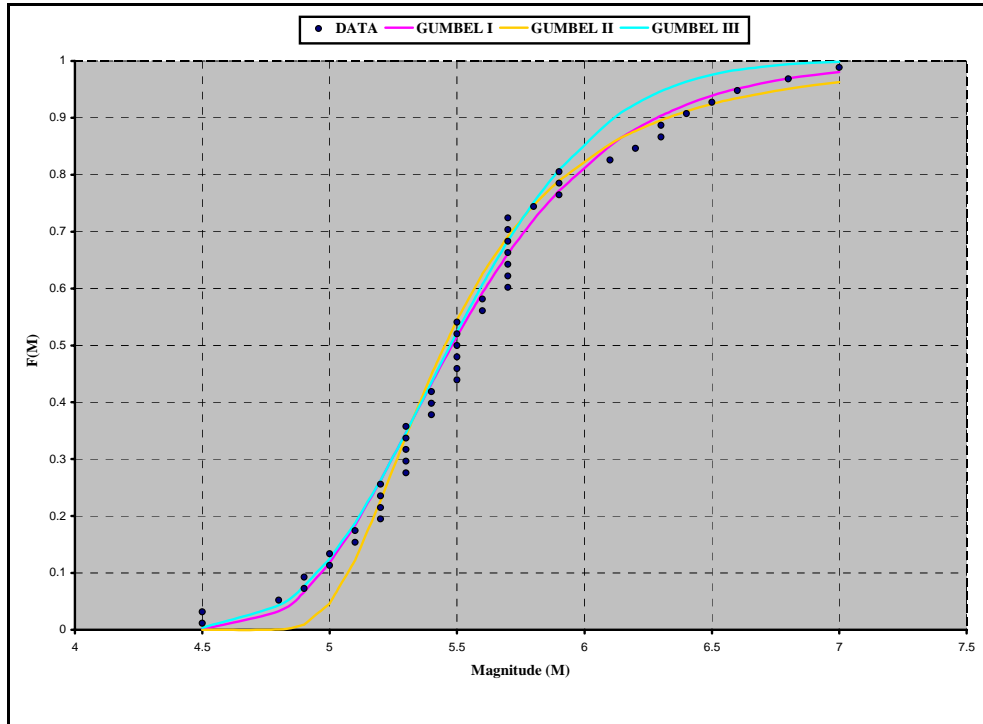
Where,  $Cov(X,Y)$  is the covariance of the two series (data-curve).

The results for the correlation factors are:

- Gumbel I ( $\alpha = 2.35, u = 5.32$ ), correlation factor:  $\rho_{x,y} = 0.9942$

- Gumbel II ( $\varepsilon = 4.0, u = 5.32, k = 4.0$ ), correlation factor:  $\rho_{x,y} = 0.9900$
- Gumbel III ( $\omega = 8.0, u = 5.32, k = 6.4$ ), correlation factor:  $\rho_{x,y} = 0.9949$

Although all three distributions show excellent correlation factors, the best correlation with  $F_{xi}$  was found with Type III distribution, as the factor is the nearest one to the ideal value  $\rho_{x,y} = 1$ .



**Figure 2.3: Gumbel I, II and III distributions.**

Discussion on the application of the different approaches (deterministic-probabilistic) is centered in the purpose of assessment, i.e. the type of the building or facility to be considered at risk. As the deterministic approach estimates the past maximum event to occur, defines the worst-case scenario for a specific zone based on source potential and the shortest distance to the interest location. The purpose in this case might be oriented towards the design of a large dam or a nuclear power plant, i.e. structures for which failure could have catastrophic consequences. On the other hand, probabilistic approaches characterize the ground motion that a given site will experience in the future. Where “... *information is numerically integrated using probability theory to produce the annual frequency of exceedance of each different ground motion level for each ground motion parameter of interest ... approach is compatible with current trends in earthquake engineering and development of building codes, which have embraced the concept of performance based design ...*” [Somerville, 2000]. Performance Based Design (PBD) is a strategy for seismic analysis of structures, which assumes, based on annual probabilities of occurrence for different earthquake sizes, different performance or behavior levels for constructions [Priestley, 2000].

In [Nisar and Golesorkhi, 1998] a comparison of response spectra from probabilistic and deterministic seismic hazard analyses has been performed for six major projects, five in California (high seismicity zone) and one in New Mexico (low seismicity zone). In high seismicity zones, ratio for both spectra induces to conclude that probabilistic analyses result in computed response spectrum higher than the mean deterministic spectrum for the scenario earthquake. In low seismicity regions, estimates of ground motion based in deterministic

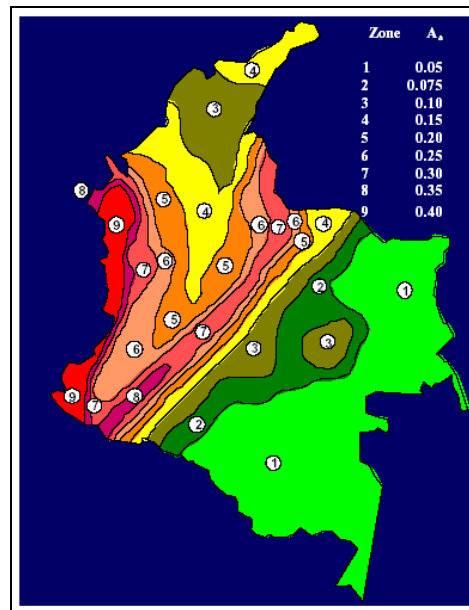
approach are higher than those based in probabilistic methods. Conclusions expose that to establish a seismic design criteria, a three-step procedure must be followed:

1. Initial hazard level must be established, based on factors such as the importance of the structure and its design life.
2. Both probabilistic and deterministic approaches must be performed to estimate site-specific response spectra.
3. Comparison of probabilistic with deterministic spectra must be performed in order to verify which of the two estimates a larger site-specific response spectrum, in each case different criteria will be used:
  - Probabilistic larger than deterministic: probabilistic estimates should be capped by deterministic estimates (Mean or 84<sup>th</sup> percentile); otherwise, probabilistic estimates should be used directly.
  - Deterministic larger than probabilistic: for non-essential facilities, the mean deterministic spectrum may be used; in case of essential facilities, an 84<sup>th</sup> percentile of deterministic estimate must be applied.

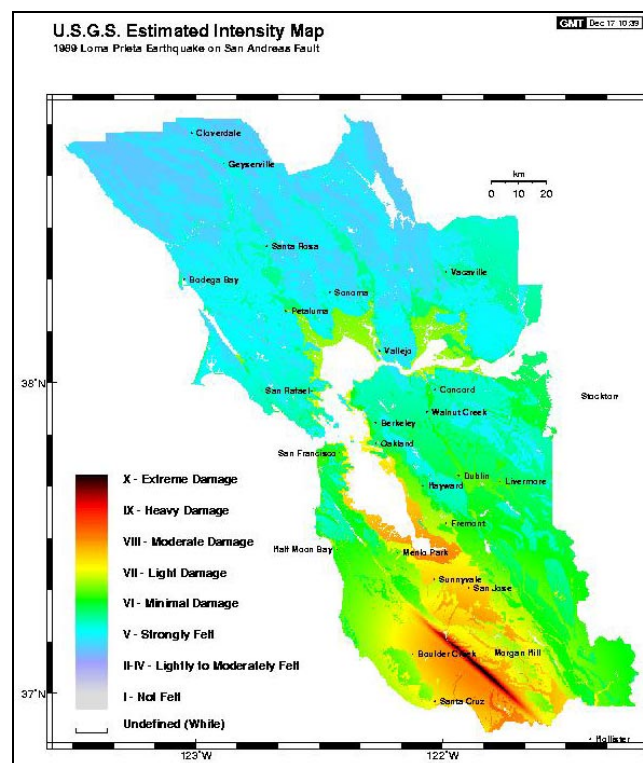
The previous statements point towards the application of both approaches in order to establish a comparison through the ground motion parameters estimated for each one. The choice is based in the values of the parameters and the purpose of application (essential or non-essential facilities).

Results for seismic hazard assessments are generally seismic hazard maps, where all information is shown in the form of zoned parameters such as: horizontal ground acceleration, Intensity or response spectra (acceleration, velocity and/or displacement). A horizontal ground acceleration hazard map is shown (Map 2.1), the distribution of effective Peak Ground Acceleration (PGA) in rock for a 475 years Return Period defines nine zones in Colombia, each one with an expected PGA level, where the greatest values concentrate over the northwestern coast of the Pacific Ocean. The distribution of macroseismic intensities over a zone or region may be deduced based on information for a single event or several events, Map 2.2 is another example showing the estimated intensity distribution expected for the repeat of the 1989 Loma Prieta Earthquake which was a  $M = 7.1$  event on the Saint Andreas fault.

Response spectra maps describe the corresponding parameters related to a probability of exceedance in a time lapse; For instance Map 2.3 shows the 2% probability of exceedance in 50 years for a damped (5%) Pseudo Spectral Acceleration at 0.2 seconds on firm ground, corresponding to Canada, as part of the National Seismic Hazard Maps for the Canadian Territory.



Map 2.1: Effective Peak Ground Acceleration in rock (return period of 475 years) for Colombia [AIS, 3Ingeominas and Uniandes, 1996].

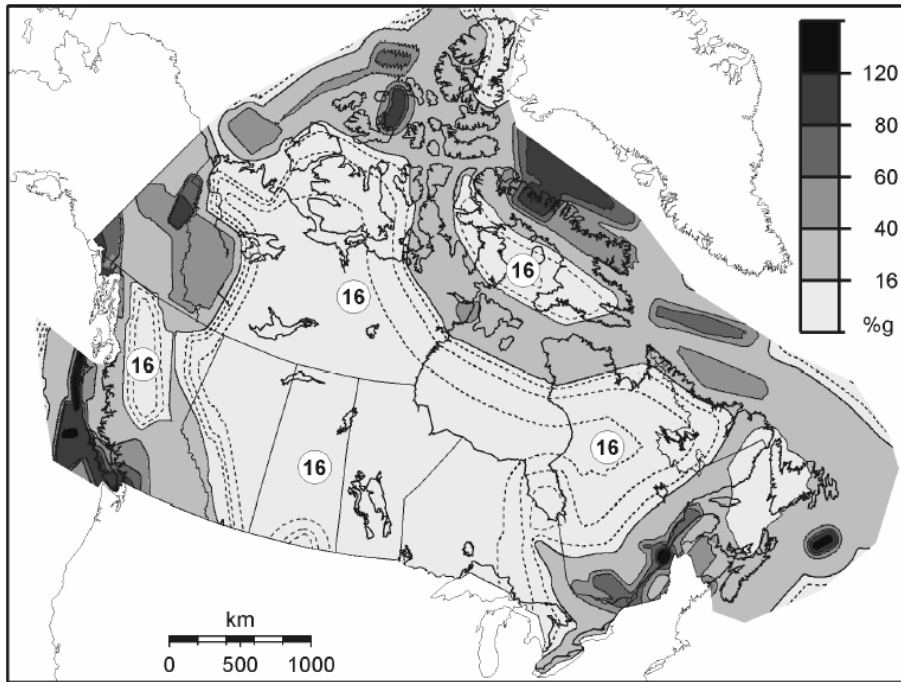


Map 2.2: Estimated Intensity map for the 1989 Loma Prieta Earthquake [USGS, 2002].

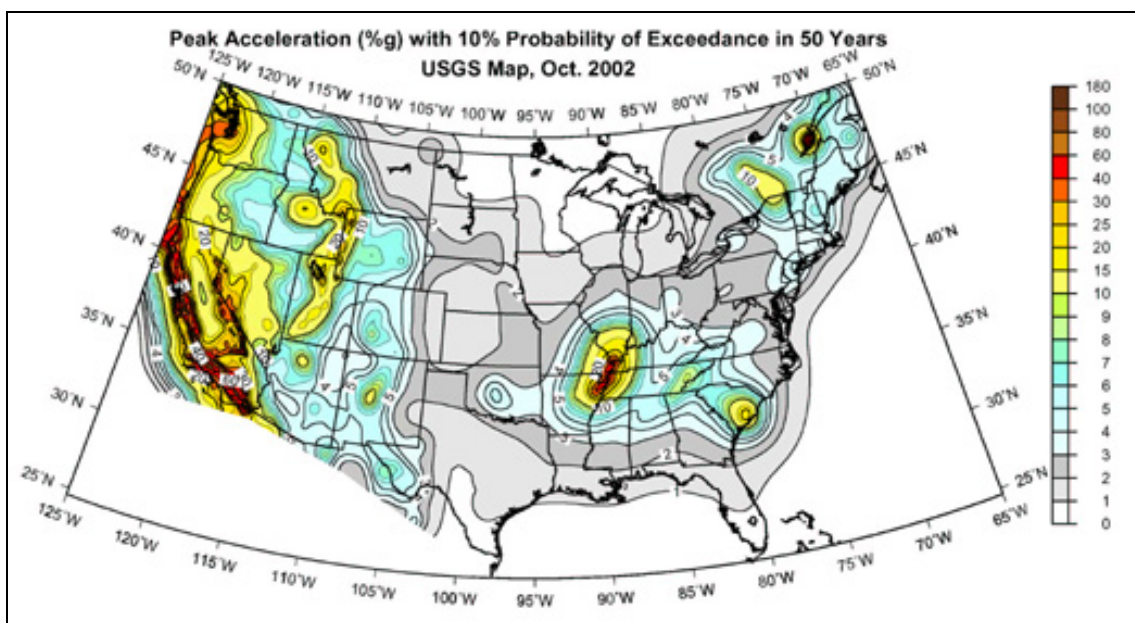
A very complete suite of data concerning national seismic hazard is that of the United States of America (USA), which through the USGS (United States Geological Survey) has compiled and treated sets of data for the entire USA territory producing maps, charts and tables that describe the different parameters (Peak Ground Acceleration, Spectral Acceleration) used in seismic hazard. The National Seismic Hazard Mapping Project (which may be found at: <http://geohazards.cr.usgs.gov/eq/index.html>), is the division in charge of producing the US

national maps showing information on earthquake ground motion values having a specified probability of being exceeded in 50 years, e.g. Peak Acceleration (%g) with 10% probability of exceedance in 50 years (shown in Map 2.4). The ground motion values are used for reference in construction design for earthquake resistance and may be used to assess relative hazard between sites (when making economic and safety decisions).

Actually, the use of GIS (Geographical Information Systems) configures a very clear and effective way of visualizing information; most of the assessments are currently represented by means of this tool, where databases are efficiently managed and visualized.



Map 2.3: 2%/50 year seismic hazard for 5% damped PSA 0.2 seconds, on firm ground, for Canada [Adams et. al., 2000].



Map 2.4: Peak Acceleration (%g) with 10% Probability of exceedance in 50 Years [Frankel et al., 2002].



### 2.4.3 Seismic Vulnerability

Vulnerability represents the sensibility of a certain element at risk to a determined hazard, or in other words and as stated previously: the degree of threat that a natural hazard may induce to a certain element. The core problem is then, the design of a parameter able to measure this threat degree; many approaches exist to the moment using different indexes which in some way describe the behavior of a certain construction when subjected to a determined seismic event. Once again, a considerable quantity of parameters is present in assessment procedures, thus a very careful definition of the element to be assessed and how it is modeled must be performed. Seismic vulnerability has a direct relationship with seismic damage estimation, i.e. how will certain expected events produce different levels of physical degradation to constructions.

General procedure for building damage estimation separates -for evaluation purposes- nonstructural from structural elements; the level of degradation depends on much on the effects over the latter. Generally, degradation of non-structural elements may not be considered as a threat to building integrity, while in the other hand, damage to structure may lead to partial or total collapse, compromising physical integrity of the building. Damage categorizations are carried out through several damage scales; assessments are performed by means of charts that show graphically the possible degradation levels in building types after an earthquake has occurred. Two examples of these damage scales are:

- The European Macroseismic Scale Damage Charts for Masonry and Reinforced Concrete Buildings. Five damage stages are described, from Negligible to Slight Damage (no structural damage) to Destruction (very heavy damage). The EMS-98 damage charts are shown in Table 2.1.
- The Federal Emergency Management Agency (FEMA) reports: FEMA-306 (Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual) [FEMA, 1998, a], and FEMA-307 (Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources) [FEMA, 1998, b]. The FEMA-306 report provides the guides for evaluating damage and analyzing future seismic performance, through component damage classification guides and test and inspection guides. The FEMA-307 report contains supplementary information including results from a theoretical analysis on the effects of prior damage on SDOF mathematical models, also, additional information on the component guides and an example of the application of the basic procedures.

Classification for damage is generally made over the basis of several damage levels, ranging from undamaged buildings to destruction or total collapse; in some cases grading of the scale depends on the consensus of expert opinions and post-earthquake surveys in damaged buildings. A unified damage scale to be used worldwide does not exist; differences in construction practices and materials, as well as damage patterns depending strongly on building types, makes of damage a sort of national parameter [EMS, 1998; Okada and Takai, 2000; Schwarz et al., 2000; Okada and Takai, 2004; Bird et. al., 2004].

Although the premise stated previously represents an actual problem in damage estimation, several strategies linking damage with elastic and inelastic structural behavior are used to evaluate possible degradation through parameters pertaining to Capacity/Demand Ratios for the considered structures. Parameters used are defined as *Damage Indices (DI's)*, which quantify structural performance or damage limit states through a normalized quantity that will be zero if the structure remains elastic and one if there is a potential of structural collapse, i.e. when the capacity of the building is exhausted ( $0 \leq DI \leq 1$ ). Intermediate structural performance states will fall in between zero and one, i.e. minor, moderate and major damage.

Seismic vulnerability as directly related to damage confronts similar difficulties in assessment; the parameters comprise national characters, and a worldwide categorization for each building type is yet not available. In general, assessing seismic vulnerability implies the creation of vulnerability factors or indexes associated with damage levels in building types, having different expressions such as: vulnerability functions, damage probability matrices or damage probability distributions, all related to parameters that describe the power of the earthquake. Several methodologies for assessment use different approaches to vulnerability, as evaluation techniques, two general strategies based on how vulnerability is inferred exist: *Observed Vulnerability (OV)* and *Theoretical Vulnerability (ThV)*.

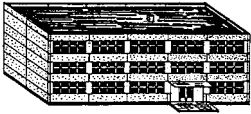



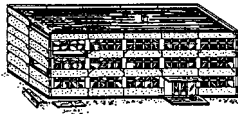





EMS-1998				
Damage Designation	Description for Building Types			
	Reinforced Concrete		Masonry	
	Damage Description	Damage Illustration	Damage Description	Damage Illustration
<b>Grade 1:</b> Negligible to slight damage. (No structural damage)	Fine cracks in plaster over frame members or in walls at the base. Fine cracks in partitions and infills.		Hairline cracks in few walls; fall of small pieces of plaster only. Fall of loose stones from upper parts of buildings in very few cases only.	
<b>Grade 2:</b> Moderate damage. (Slight structural damage, moderate nonstructural damage)	Cracks in columns and beams and in structural walls. Cracks in partition and infill walls; fall of brittle cladding and plaster. Falling mortar from the joints of wall panels.		Cracks in many walls; fall of fairly large pieces of plaster; partial collapse of chimneys.	
<b>Grade 3:</b> Substantial to heavy damage. (Moderate structural damage, heavy nonstructural damages)	Cracks in columns and beam column joints of frames at the base and at joints of coupled walls. Spalling of concrete cover, buckling of reinforced rods. Large cracks in partition and infill walls, failure of individual infill panels.		Large and extensive cracks in most walls; Roof tiles detach. Chimneys fracture at the roofline; failure of individual non-structural elements (partitions, gable walls).	
<b>Grade 4:</b> Very heavy damage. (Heavy structural damage, very heavy nonstructural damage)	Large cracks in structural elements with compression failure of concrete and fracture of rebars; bond failure of beam reinforced bars; tilting of columns. Collapse of a few columns or of a single upper floor.		Serious failure of walls; partial structural failure of roofs and walls.	
<b>Grade 5:</b> Destruction (very heavy structural damage)	Collapse of ground floor or parts (e. g. wings) of buildings.		Total or near total collapse	

Table 2.1: Damage Chart for European Macroseismic Scale [EMS, 1998].

**Observed Vulnerability:** observed damage in post-earthquake assessment is treated statistically to establish a parameter that relates building types and damage grades (generally

referred to macroseismic scales damage grades) at the level of impact suffered. This parameter describes the sensitivity to damage for different building types, related to seismic events exertion. Actually, post-earthquake surveys are being performed as exhaustively as possible, so to measure this distribution of impact at different sites with different damage levels. For this purpose, special equipment and teams must be deployed after earthquake impact, measuring aftershocks and local site responses related to Macro seismic evaluation of damage in buildings (Intensity assessments) so to obtain vulnerability parameters. Several authors, [Schwarz et. al., 2000; Cherubini et. al. 1999; Okada and Takai, 2000; Shibata et al., 2000, Multinovic and Trendafiloski, 2003; and; Giovinazzi and Lagomarsino, 2004] represent examples of this approach, using, in different manners but with similar general principles, the Observed Vulnerability methodology. A general strategy for vulnerability assessment widely used by researchers is presented in this chapter.

**Theoretical Vulnerability:** also defined as calculated vulnerability; assessments for damage are performed using numerical or mechanical models. These approaches, although very developed, still confront uncertainties at present, related not only to model generation but also to the input to which the model will be subjected. Numerical models characterize the building's most relevant features in dynamic behavior; completeness and consequently the assertiveness of models depend on the levels of detailing performed, and the assumptions made for materials strengths. The most problematic and complex models are those made for existing buildings, where idealizations must be performed depending on the knowledge of As-Built conditions in buildings [Holmes, 2000]. Mechanical modeling implies the reproduction of idealized building types in dynamic testing laboratories; once again, the knowledge of As-Built conditions is a strong issue determining the assertiveness of model representation, and also must be performed analyzing cumulative damage on every model due to the economical impracticability of building identical models for every possible seismic input [Coelho et al., 2000]. Examples of this methodology can be found in Vulpe et al. (2000), Coelho et al. (2000) and Lafuente et al. (2000), where the use of numerical and mechanical models serves to establish several damage-vulnerability relationships for different building types in countries around the world. For theoretical vulnerability, assessment models must be calibrated and verified with observed damage in every case; occurring earthquakes are then excellent opportunities to perform these procedures, but it implies a detailed knowledge of the building characteristics (through previous surveys or by means of structural plans). Due to this detailed analysis of the buildings, such theoretical methods are unfeasible to be applied over an extended group of buildings.

Many of the actually used methodologies may not fall completely into one or other of the previous categorizations exposed, instead a combination of both approaches are generally used, providing sets of useful data that complement each other.

An example of damage categorizations related to buildings performance (as a direct link between seismic action and damage) are presented in Bozorgnia and Bertero (2001), where a series of shaking and damage parameters for studies performed in the Southern California region are exposed. Through a post-earthquake survey, parameters for ground motions are estimated: 1- Peak Ground Acceleration (PGA), 2- Peak Ground Velocity (PGV), 3-, 4- and 5- Elastic Spectral Acceleration at periods 0.3, 1.0 and 3.0 sec respectively; and the instrumentally derived Seismic Intensity. Six maps containing each ground motion description parameter are created. Response and damage parameters for buildings are estimated through Damage Indices variations with structural periods for a series of elastic and inelastic SDOF systems subjected to a recorded ground motion. The used damage Indices ( $DI$ 's) are:

- **Displacement Ductility:** ductility ( $\mu$ ) is defined as the ratio between maximum displacement of an inelastic SDOF system and the yield displacement, i.e. the displacement that exhausts the material of the structure. The Spectrum represents the variation of  $\mu$  with period, providing useful information about the general inelastic response behavior.
- **Interstory Drift Ratio** (also called, Story Drift Ratio): represents the ratio of the maximum story displacement over the story height. Interstory drift ratios produced by recorded ground motions may be estimated by using the displacement ductility ratio. The spectrum represents the variation of Story Drift Ratio with period.
- **Hysteretic Energy ( $E_H$ ):** is a measure of the inelastic energy dissipation produced by earthquake ground motion. It includes cumulative effects for repeated cycles of inelastic response and the effects of strong-motion duration. Spectrum represents the variation of equivalent hysteretic energy velocity,  $V_H = \left(\frac{2E_H}{M}\right)^{\frac{1}{2}}$  (where  $M$  is the mass of the equivalent SDOF system), with period.
- **Housner Spectrum Intensity ( $SI$ ):** defined as the area under the pseudo-velocity response spectrum over a period range from 0.1 to 2.5 sec. It describes a measure of the intensity of ground motion for elastic structures.
- **Improved Damage Indices:** two damage indices for generic inelastic SDOF systems are based in damage, as related to monotonically increasing lateral deformation, combining normalized hysteretic energy and displacement ductility in formulation. General expressions are:

$$DI_1 = \left[ \frac{(1 - \alpha_1)(\mu - \mu_e)}{(\mu_{mon} - 1)} \right] + \alpha_1 \left( \frac{E_H}{E_{Hmon}} \right) \quad \text{eq. 2.20}$$

$$DI_2 = \left[ \frac{(1 - \alpha_2)(\mu - \mu_e)}{(\mu_{mon} - 1)} \right] + \alpha_2 \left( \frac{E_H}{E_{Hmon}} \right)^{\frac{1}{2}} \quad \text{eq. 2.21}$$

where,

$$\mu = \frac{u_{max}}{u_y} = \text{Displacement Ductility}$$

and,  $u_{max}$  is the maximum displacement;  $u_y$  is the yield displacement

$$\mu_e = \frac{u_{elastic}}{u_y}$$

Where,  $u_{elastic}$  is the maximum elastic portion of deformation (i.e. maximum deformation where the system still remains in the elastic domain) and,  $u_y$  as defined above. Depending on the values of the yield displacement ( $u_y$ ),  $\mu_e$  takes the values:

$$\mu_e \begin{cases} = 1 & \text{for inelastic behaviour} \\ = \mu & \text{if the system response remains elastic} \end{cases}$$

$\mu_{mon}$  is the monotonic displacement ductility capacity

$E_H$  is the hysteretic energy demanded by the earthquake ground motion

$E_{Hmon}$  is the hysteretic energy capacity under monotonically increasing lateral deformation, and

$$0 \leq \alpha_1 \leq 1, \quad 0 \leq \alpha_2 \leq 1, \text{ where } \alpha_1 \text{ and } \alpha_2 \text{ are constants between 0 and 1}$$

Advantages in using these latter damage indices rely in their ability to describe several types of structural behavior; i.e. they will be zero if the structure remains elastic ( $\mu = \mu_e$ ) and one when the maximum deformation capacity is reached under monotonically increasing lateral deformation. If  $\alpha_1 = 0$  and  $\alpha_2 = 0$ , the damage indices  $DI_i$  ( $I = 1, 2$ ) are only related to the maximum plastic deformation (as no hysteretic energy is involved in the system), on the other hand, if both  $\alpha_1$  and  $\alpha_2$  are equal to the unity the damage indices will be only related to the hysteretic energy dissipation.

Repeated cycles of inelastic deformations and strong-motion duration also influence the damage spectra. However, to accurately relate the computed damage with the real damage in structures, an Up-to-date inventory of existing buildings must be performed, with special attention to parameters considered in the  $DI$ 's. The knowledge of As-Built features is a *sine qua non* condition in methodology, as the scope is the theoretical vulnerability.

Methodologies for damage assessments and vulnerability estimations are diverse and may be used in different cases, depending on the level of data available (quantity and quality) and in the purpose of assessments. Earthquake experiences, such as, for example, the Kocaeli, August 17<sup>th</sup> 1999 in Turkey, the Chi-Chi, September 21<sup>st</sup> 1999 in Taiwan, the El Quindío, January 25<sup>th</sup> 1999 in Colombia, the Bam, December 26<sup>th</sup> 2003 in Iran, and the West Coast of Sumatra December 26<sup>th</sup> 2004 earthquakes; have shown that non-engineered constructions, which are very extended over many regions, have suffered great amounts of damage. In these cases, the main cause of injuries and casualties is the unawareness of seismic risk, which produces an increment of seismic vulnerability of the built environment in time.

It is clear that although an enforcing code may be available, it is a necessary but not sufficient condition in prevention and mitigation, because its application is performed in newly designed and constructed buildings with the contribution of specialized professionals and experts. Informal buildings, on the other hand, are not designed and/or built according to codes; consequently, the seismic performance is uncertain. In developing countries, where urban growth is not planned or controlled, the possibility of inadequate seismic performance of buildings is very high. For example, in many Latin American capitals, informal settlements may house up to 40% of total population of the cities. Self-construction or code-predating building procedures on informal settlements generally do not consider seismic resistant features; the need for a shelter with the minimum cost in time and money is the fundamental priority in these cases. Any other consideration on building is a luxury that inhabitants are not willing to cover. Assessing informal non-engineered building types is a very difficult task, being the primary problem to sensitize inhabitants with seismic risk and the possible consequences of earthquake impacts. Additional problems arise in the analyses of materials, structural configurations, structural and non-structural elements, that in the case of built constructions is not simple or straightforward, because all data needed must be obtained directly from the study field, and modeling (theoretical or mechanical) is not always feasible. An effort pointing towards a better comprehension of this problem is actually being carried out by the “*EERI/IAEE Encyclopedia of Housing Construction Types in Seismically Prone Areas of the World*”, a joint project of the Earthquake Engineering Research Institute (EERI), the International Association of Earthquake Engineering (IAEE), and the Engineering Foundation in New York City. Objective is to collect information pertaining vulnerability of housing construction types in many countries worldwide, so to build a worldwide database for housing building types [EERI/IAEE, 2005].

### 2.4.3.1 Vulnerability Index Method

A very useful methodology is that of the vulnerability index method, expressing the damage-vulnerability relationship as a normalized index depending on several parameters. Utility of this methodology relies in its ability to evaluate a great number of buildings through a fast screening procedure performed with simplified assessment forms. Developed by the GNDT (Gruppo Nazionale per la Difesa dai Terremoti), after Benedetti and Petrini, (1984), general approach consists in the analysis of a great database built up by assessments of after impact consequences on buildings using the *First Level Assessment Form* [GNDT, 2001a]. Through acquired data analysis and with the help of experts opinions, relationships between building damage and ground motion parameters are established, defining the seismic damage variation for the types of buildings assessed, under the ground motion parameters considered. These relationships are called *vulnerability functions*. In Figure 2.4, an example of a vulnerability function for MSK intensity  $I = VII$ , is shown for masonry buildings in Spain, based in damage observation (application of the *First Level Assessment Form*), the dashed lines are the vulnerability functions for MCS intensities ( $I = VI$ ,  $I = VII$  and  $I = VIII$ ) obtained by Angeletti et al 1988, in Italy, using the same approach. The vulnerability indices (*INDICE DE VULNERABILIDAD*) are related with the damage indices (*INDICE DE DAÑO*) observed in Spain through samples (points in the figure); the resulting curve is a numerical fit of these points (*REGRESION MSK*).

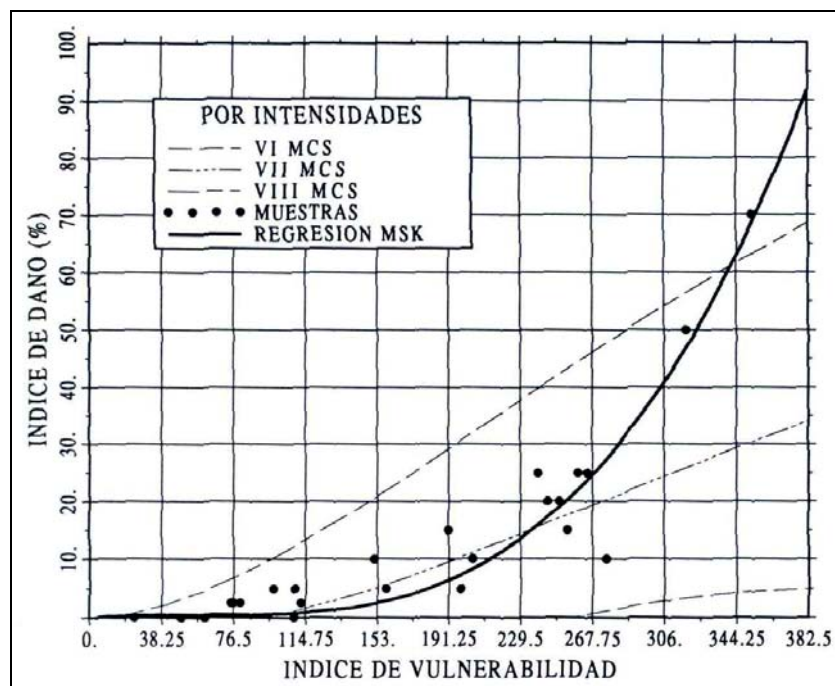


Figure 2.4: Observed vulnerability function for Spain at MSK Intensity  $I = VII$  [Barbat, 1995].

A *Second Level Assessment Form* [GNDT, 2001b] is created with these definitions, so to evaluate vulnerability in existing buildings, independently of seismic damage presence (based in the building's characteristics). Eleven parameters have been identified in order to describe the main seismic features of the building's types; they are grouped in three categories: (1) structural and nonstructural elements distribution and strength, (2) overall shape of the building, and (3) site conditions. In Table 2.2, the Second Level Assessment Form parameters and a brief explanation for two different building types (Masonry and Reinforced Concrete) are shown.

The general procedure for vulnerability index assessment establishes a numerical categorization scale for each parameter  $K_i$  (usually three quality grades: from best, A, to worst, C, about seismic performance) and a weight  $W_i$  depending on the level of influence of the parameter in the total vulnerability. The sum of these eleven parameters times the corresponding weights determines the numerical value of the vulnerability index  $I_V$ :

$$I_V = \sum_{i=1}^{11} (K_i \times W_i) \quad \text{eq. 2.22}$$

Values for  $K_i$  and  $W_i$ , are subjective and depend on opinions from experts, but far from reducing the method's reliability introduces a consensus feature in vulnerability assessment.

Advantages for this approach rely not only on applicability to several sub typologies within any of the two building types, but also to different structural qualities within the sub typology. On the other hand, an extensive survey must be performed in order to obtain data from the field; e.g., the GNDT database contains data from about 13,000 buildings (11,433 masonry and 1,409 reinforced concrete structures) surveyed over many Italian regions [Cherubini et al., 1999]. It is important to remark that observed damage is essential to methodology, thus, application in low hazard areas, or in areas where impacts have not been assessed properly will require additional research in damage modeling (Theoretical Vulnerability). Some known cases fall into the last application of the method. The research carried by [Yépez, 1996], is based on simulation of vulnerability functions and its calibration with observed vulnerability functions. Observed seismic damage, occurred in the Province of Almería (Spain) for masonry buildings, served as the basis to an observed vulnerability function. In addition, by means of Monte Carlo simulation method, two typologies (Masonry and Reinforced Concrete) buildings characteristics were simulated and forwardly, the possible damage for the building stock was computed. Simulated vulnerability functions for these two typologies were then calibrated by comparison to observed vulnerability functions. Other authors [Barbat, 1998; and Mena, 2002] have used the previous approach and results to continue the advance in application of simulated vulnerability functions in assessing seismic risk for urban areas.

#### 2.4.4 Seismic Risk and Seismic Risk Scenarios

Integrating all the data acquired from hazard and vulnerability assessments in a unique parameter is defined as *risk assessment*; the objective is to describe the possible losses or damage in elements at risk within a site, generated by particular ground movement conditions in a determined exposure time. Objectives for seismic risk assessments are oriented to fulfill information requirements and help to establish criteria for three fundamental strategies: prevention, mitigation and preparedness, where each one of these requires a set of decisions and policies to guarantee a certain level of safety in the urban environment.

Approaches to risk estimation may be different not only depending on methodologies used in hazard and vulnerability assessments but in the risk conceptualization used (elements at risk considered, relationship between elements). As stated previously in this chapter, many different elements may be considered, and this consideration constitutes the cornerstone of risk assessment.

Parameters for Masonry	Brief explanation	Parameters for Reinforced Concrete	
Resisting System Type and Organization	Description related to plan organization of structural elements, plan sketches	Resisting System Type and Organization	
Resisting System Quality	Categorization for vertical and horizontal structural types based on materials used	Resisting System Quality	
Conventional Seismic Strength	Calculated parameter, describes capacity depending on structural configuration, material strength, preservation state and statistical evaluation	Conventional Seismic Strength	
Location and Soil Condition	Classification for foundation positioning and local soil conditions	Location and Soil Condition	
Horizontal Structures	Prevailing horizontal structural type and other horizontal structures. Classifies diaphragm load distribution capacity over vertical structural elements	Horizontal Diaphragms	
Plan Shape	Categorization based in plan configuration of the building, symmetric shapes are considered ideal	Plan Configuration	
Regularity in Elevation	Categorization based in elevation configuration of the building, regular elevations are considered ideal	Elevation Configuration	
Maximum Distance between Walls	Describes crosswall distances, so to control possible out of plane bending in master walls	Description and location for low ductility elements	Low Ductility Structural Elements
Roofing System	Categorization based in roofing structure and connectivity with the walls		
Nonstructural Elements	Describes the presence of architectural elements and its connectivity with the structure	Nonstructural Elements	
Preservation State	Description of structural materials integrity	Preservation State	

**Table 2.2: Parameters for Masonry and Reinforced Concrete Building Types [GNDT, 2002].**

Three general groups of elements govern the possible degradation of an urban environment: *Physical*, *Social* and *Economic* elements, where the physical takes relevance as the original damage generator over itself and the others. Many authors have discussed this issue contributing with approaches tending to establish a taxonomy of the factors influencing degradation at urban settlements [Cardona and Hurtado, 2000; Yang, Xiao and Zhu, 2000; Mujumdar, 2000; Davidson and Shah, 1998; Davidson et. al., 2000; Di Pasquale et. al., 1998]; the agreement is that all the three elements must be considered in any assessment procedure so to estimate accurate impact consequences. A very useful conceptual framework (holistic approach) that enlightens to some extent the factors contributing to a settlement's earthquake disaster risk is provided by [Davidson and Shah, 1998], five main factors contribute:

- **Hazard:** represents the geological phenomena that may trigger events of an earthquake disaster, i.e. the demand to which a city may be subjected. Within this factor, ground shaking and collateral effects (ground failure, slide and rupture) are considered.



- **Exposure:** represents all built facilities, population, economy and activities associated with them in each local area, i.e. a list of everything that is subjected to the physical demands of hazard.
- **Vulnerability:** describes how easily and severely the city's exposed entities may be affected by an earthquake; including physical infrastructure, population, economy and social-political system.
- **External context:** based in the notion that damage to certain cities may affect people and activities outside these, describes the relationship between urban settlements as a network of interrelated centers.
- **Emergency response and recovery capability:** describes how formal, organized activities in the cities may cope effective and efficiently with short- and long-term earthquake impact.

The conceptual framework exposed seems very complete and useful in the sense of considering all the three general elements at risk described previously and the relationships between them. As a basis for assessment procedures, the holistic character of conceptualization requires great quantity of high quality information coming from different sources with different professional profiles. Although the holistic approach may introduce several difficulties as the complexity increases considerably in assessments, the multidisciplinary and interdisciplinary work of professionals assures an integration of many different actors, as possible, into the problem. This need for information, in quantity and quality, requires for all levels of administration (national, regional, local) up-to-date and accessible databases.

From this conceptual framework diverse numerical approaches based in probabilistic estimations for the factors have been developed in different places in the world through varied methodologies for data acquisition and treatment; having in common the establishment of a risk index as the result of integrating into one only parameter the predicted consequences of earthquake impact over the urban environment. Generally, loss estimation as a final consequence of assessments is expressed in terms of economic losses, i.e. the cost of degradation for each of the factors involved. The use of this economic expression is widely extended in methodologies because it represents a consistent, identifiable and measurable parameter.

Contributors to the process of converting the series of observations and recommendations coming from risk assessments to a set of legal and technical proposals, usually have different professional profiles (engineers, architects, geoscientists, economists, lawyers, social workers, sociologists, educators, governmental authorities, etc.), where some groups or persons may not be acquainted with the overall technical or scientific facts pertaining the problem. Thus, the decision-making process becomes complex in the sense of information comprehension and sensibility to the problem, where all actors must have a holistic vision. Consequently, it is essential for information to be presented as clear and expedite as possible, so to be understood by any person not familiarized with the seismic question, without losing quality in contents. Actually, a very useful strategy for information presentation is that of the *seismic risk scenarios*, which through the use of maps showing the possible consequences of different earthquakes illustrate how the urban environment's composing elements interact in such a case.

Seismic risk scenarios may nowadays be considered as the ultimate expression of assessments, where all data is integrated as useful and adequate information for decision-making processes. The refinement in information presentations by the use of geographical data visualization and administration tools (Geographical Information Systems, GIS) have

enhanced notoriously the versatility and diversity in generation of seismic risk scenarios, coping efficiently with adequate diffusion of useful information.

## **2.5 Summary**

Earthquakes are natural phenomena difficult to handle. The actual trends in the understanding of seismic events as sources of possible catastrophes are nowadays a science in itself, where many uncertainties arise at the moment of predicting not only the occurrence of events, but also the pernicious effects over the built environment. This intention to describe as realistically as possible the processes of earthquake generation in time, the seismic waves transmission through the earth crust, the local soil response (Seismic Hazard) and finally the behavior of constructed facilities (Seismic Vulnerability) is actually covered to a great extent by seismic risk evaluations. Each of these processes requires specialized knowledge and skilled professionals for the evaluations, as well as a great amount of suitable and high quality data.