Analysis of uncertainties associated with different approaches for earthquake risk assessment

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SUMMARY:
Since earthquake risk assessment implies randomness and uncertainty, it is necessary to find out key parameters, criteria and methodologies, according to available seismic hazard and vulnerability knowledge, to handle aleatory variability and reduce epistemic uncertainty. This paper analyzes aleatory variability and epistemic uncertainty associated with data and approaches to estimate earthquake risk in terms of variables such as probable maximum loss, risk pure rate among others, which consider different levels of detail for data to represent regional and local seismic hazard, as well as structural and non structural vulnerability of buildings. Identification of variables and criteria that controlled the effects of six real earthquakes in New Zealand (2010 and 2011), Haiti (2010), Chile (2010) and Colombia (1999), constituted an important part of the study, because it showed key issues to be taken into account to treat aleatory variability and epistemic uncertainty on earthquake risk assessment.

Keywords: epistemic uncertainty, aleatory variability, earthquake risk.

INTRODUCTION

Governments, insurers and reinsurers require earthquake risk assessment, in order to make suitable decisions to safe their solvency and count on proper protections to respond to their financial responsibilities associated with earthquakes. The most appropriate way to evaluate earthquake risk is the probabilistic approach, which corresponds to the convolution of hazard, exposure, and vulnerability, and its output is a curve relating loss against the annual frequency of exceedance. However, there are widespread misunderstandings of the scope of the probabilistic approach, misleading terminology, and lack of representative data to characterize seismic sources and/or seismogenic zones, soil profiles at the site, and structural and non-structural vulnerability, which may lead to unrepresentative results of earthquake risk, poor interpretation and improper decision making.

Evaluation of regional and local earthquake hazard, seismic vulnerability and earthquake risk implies a great responsibility to achieve sustainable recovery after earthquakes. In this way, it is necessary to take into account several sources of randomness and uncertainty on these estimations, in order to select reasonable methods of analysis adjusted to the available data in each case.

This paper analyzes aleatory variability and epistemic uncertainty related to the evaluation of the three main components of earthquake risk: regional seismic hazard, local seismic hazard, and structural vulnerability. For each component, it evaluates different level of detail of data and the corresponding kind of methodologies which may be appropriate to obtain representative results.

1. EARTHQUAKE RISK ASSESSMENT: SCOPE AND INFLUENCE OF UNCERTAINTIES

There are two basic approaches to carry out estimation of earthquake risk: deterministic and probabilistic, which take into account methodologies and criteria developed for earthquake hazard analysis. Some authors have identified important misunderstandings of the two approaches, which cause large variability and misinterpretation of this kind of analysis (Abrahamson, N.A, 2000; Bommer, J. J., and Abrahamson, N. A. (2006).

1.1. Deterministic approach

The deterministic approach selects a limited set of earthquake scenarios (magnitude, seismic source or seismogenic zone, style-of-faulting, distance from the earthquake to the site) and specified ground motion probability level (which implies selection of the number of standard deviations from the median for variables such as the ground motion level or the earthquake loss, typically either 0 or 1 standard deviation above the median). This selection of scenarios implies the use of some aspects of probability to carry out deterministic analysis, which leads to a single ground motion for each scenario considered. Many of the common problems of the state-of-the-practice of deterministic analysis are a result of inconsistent terminology or misunderstandings about its scope, for example, the fact of using some variables of probability to develop a deterministic analysis misleads to be considered as a probabilistic approach. The main characteristic of the deterministic approach is selection of specific scenarios, which implies that this approach neglects influence of the rest possible earthquakes with influence at the site.

1.2. Probabilistic approach

The probabilistic approach considers all possible earthquake scenarios (which means all possible magnitude and distance combinations associated with all seismic sources and/or seismogenic zones that influence the site) as well as all possible ground motion probability levels (according to selected number standard deviations from the median) along with their associated probabilities, and it computes the probability that any of the scenarios will produce a loss greater than a given value. The probabilistic approach leads to a loss curve, giving the probability of exceeding various earthquake loss values. In probabilistic earthquake risk assessment is clear the existence of the aleatory uncertainty, which is the inherent randomness in earthquake occurrence and ground-motion generation, and the epistemic uncertainty related to the lack of knowledge. Using the terms aleatory and epistemic leads to a more consistent use of terminology, because these terms clarify about suitable treatments for each part of uncertainty.

The probabilistic earthquake risk assessment (in terms of losses) should be the sum of the contribution of all the seismogenic zones with influence on a site. Earthquake risk curves can be obtained for each seismogenic or source zone and combined to express the aggregate earthquake risk for a particular portfolio. The probability of exceeding a particular value of earthquake loss is calculated for one possible earthquake at one possible location within a seismogenic zone and then multiplied by the probability that that particular magnitude earthquake would occur at that particular location of that seismogenic zone. The process is then repeated for all possible magnitudes and locations within the seismogenic zone, obtaining the earthquake risk curve at the site associated to a specific seismogenic zone. Finally, it is obtained the aggregate earthquake risk curve through the sum of the earthquake risk curves of each and every seismogenic zone with influence on the interest site.

The results of the contribution of each seismogenic zone to the earthquake risk are presented in terms of the probability that the earthquake loss exceeds a particular value of loss *p* in a specified future time interval, according to Equation (1).

$$v(p) = \lambda_{0M} \int_R \int_M \left(\int_0^{\infty} \Pr(\textit{Pérdida} > p / S_a) f_{S_a/m,r}(S_a / m, r) ds_a \right) f_M(m) \cdot f_R(r) \cdot dm \cdot dr \quad (1)$$

Where,

$\nu(p)$: It is the total average exceedance rate of a given value of loss p.

P(*Pérdida*>*p*/S_a): It is the probability that the earthquake loss exceeds a particular value of loss p for a given spectral acceleration S_a. This part of the equation represents the expected structural behavior under earthquake, which is the vulnerability.

$f_{S_a}(S_a / m, r)$: It is the probability density function of spectral acceleration at the site, given the occurrence of an earthquake of magnitude m at a distance r. This part of the equation represents regional and local seismic hazard.

$f_M(m)$: It is the probability density function of magnitude m.

$f_R(r)$: It is the probability density function of earthquake distance r.

Each component of the Equation (1) may be estimated through several approaches and methodologies depending on the available information of earthquake sources and/or seismogenic zones, the ground motion prediction equations at rock level applicable to those seismogenic zones, the representative transfer functions of existing soil profiles at the site to estimate ground surface motions, and the vulnerability functions to represent the expected performance of structures under earthquake ground surface motions. In the numerals 2 to 5 of this paper several aspects are discussed, in order to identify parameters, methodologies and criteria that can be useful in reducing overall uncertainties.

Epistemic uncertainty is commonly handled through a logic tree framework. A logic tree is composed by either-or branches, where each branch represents a credible model. In this way, epistemic uncertainty is considered by specifying the credible alternative models for the probability density functions, vulnerability functions, transfer functions, attenuation relations, and activity rates (Abrahamson, 2000). According to the applicability and credibility of each model, an expert or an expert group assigns a degree-of-belief value or weight to each branch of the logic tree. For the calculation of earthquake risk curves, these branch weights are subsequently used as subjective (conditional) probabilities. Then, it is necessary to be bound by the rules of probability calculus to assign logic tree weights, in order to avoid logical inconsistencies, because tree branch weights will lead to some unexpected and most likely unintended results. These results might actually look formally correct (because of the normalization), but if normalization is seen only as a matter of convenience, and not as a part of a theoretical framework in which this normalization must reflect the fact that the model set is mutually exclusive and collectively exhaustive, the normalization process can lead to an apparent insensitivity to the weights. Treating the weights as probabilities from the start would mean that a weight must reflect a logically consistent degree-of-belief (Scherbaum, F. and Kuehn, N.M., 2011; Abrahamson, 2000).

On the other hand, aspects associated with aleatory variability are considered into the standard deviation of probability density functions (Abrahamson, 2000). In probabilistic earthquake loss analysis the influence of the aleatory variability is incorporated by directly integrating across scatter of the probability density function as part of calculating the exceedance frequency of different levels of loss (Scherbaum, F. et al., 2005). Taking into account that our understanding and knowledge of available models for the median values may be quite different from those for the aleatory variability of earthquake risk, the separate treatment of epistemic and aleatory uncertainty has its difficulties (Scherbaum, F. et al., 2005). Therefore, it may be desirable to use the probabilistic approach defining separate logic trees for median values (epistemic uncertainty) and sigma values (aleatory variability), through a composite earthquake risk model, which contains the same information as the complete set of end-branch models, just arranged differently (along median and aleatory variability scales). Composite earthquake risk model treats uncertainties in a clear way, considering the dependence of models represented by branches of a logic tree.

2. REGIONAL SEISMIC HAZARD

2.1 Definition and delimitation of seismic sources and/or seismogenic zones

A seismogenic zone is defined as a geologic feature or group of features with similar style of deformation and tectonic process, where it is possible to infer relationships between the deformation and the seismicity. The definition and delimitation of seismogenic zones in regions with sufficient information, is based on spatial distribution of epicenters of earthquake catalogs, as well as on available geological, geodetic and paleoseismic evidences related to earthquake activity. In seismic sources with no-sufficient information to correlate past earthquakes with known geological structure, the superimposed assignation of epicenters to the source implies deep uncertainties. In these cases it is more suitable to define bigger zones, which cover a group of geological features with similar style of deformation and tectonic setting. In this way, a relationship between this deformation, historical and instrumental earthquake activity can be inferred.

Figure 1 represents the basic steps to define and delimitate seismogenic zones, which is based on the approach of type A, type B and type C zones adopted for Working Group on California Earthquake Probabilities (WGCEP, 1995). These methods and criteria classify seismogenic zones, which can be delimitated as geologic feature or group of features respectively, depending on the quality and quantity of available information. Type A zones are seismic sources composed by fault segments with sufficient paleoseismic data. The level of information and knowledge about these zones allows the application of segmentation models to characterize faults, and the estimation of conditional probabilities for earthquakes on these faults. Type B seismogenic zones are those that contain major faults with measurable slip rates but inadequate data on segmentation, displacement or last earthquake. The available information of this type of zones does not justify a conditional probability analysis, because its results will not be representative of their expected behavior. Some examples of type B zones are the following: fault segments where there is many doubts about whether it ever ruptures as a single segment or it fails by triggering of neighboring segments; seismogenic zones characterized by complicated histories, so the slip rate can not be explained adequately by repeated recurrence of a single characteristic earthquake; seismogenic zones that present aseismic periods that can not be represented with a recurrence model. Type C zones correspond to seismogenic regions that are not dominated by any single major fault, but they may contain diverse or hidden faults. This type of seismogenic zones may be applicable for regions characterized by the occurrence of inter-plate and intra-plate earthquakes.

2.2 Selection of the geometry to represent seismogenic zones

The suitable geometry to represent seismogenic zones depends on the quality of available information about their tectonic processes. The seismicity within each zone can be modeled as: (i) 3D or volumetric sources: These are applicable to type C zones, which include regions that are not dominated by any single major fault, regions that may contain diverse or hidden faults, regions characterized by contact among plates, or regions where seismicity can not be associated with known seismic sources, (ii) Two-dimensional or areal sources: These models are used to represent well-defined fault planes, on which earthquakes can occur at different locations. Areal sources are characterized by location and geometry, earthquake recurrence rates and maximum earthquake magnitude. Areal sources are often used to model type A zones. Depending on the available information in each case, type B zones can be modeled using areal or volumetric models. It is possible to approximate an areal source, like a fault plane, as a linear source when its depth is sufficiently small that variations in the hypocenters of earthquakes have little incidence on distances between any point of the areal source and the site. This kind model is also used to model finite rupture lengths. Linear sources are characterized by location, e.g. latitude and longitude of the points bounding each segment. Seismic source zones related with volcanic activity may be represented as point sources. This model is also used to represent short and well-defined fault, when its depth is sufficiently small and the distance between any point along its length and the site is very similar. Furthermore, point sources are also useful to model earthquakes associated with small rupture length of a fault.

It is necessary to note that the following stages of the seismic hazard assessment, related to characterization of seismogenic zones (epicenter location, occurrence time and seismic intensity), are based on delimitation of type A, type B and type C zones. This implies that there are different approaches to characterize some parameters of sources, depending on the knowledge about them.

2.3 Branches on logic trees for fault segmentation

A common problem with logic trees is that the alternative models about seismic source or seismogenic zone characterization and ground motion attenuation are not complete. This is most common in seismic source characterization, such as branches on logic trees for fault segmentation, for example a fault that sometimes rupture in individual segments and sometimes rupture as multiple segments mechanism. The correct way to treat the uncertainty associated with fault segmentation is to have two branches in the logic tree: one branch represents the unsegmented fault, and another branch considers the fault composed by *n* separate segments. Each branch in the logic tree needs to cover the entire fault length, in that way, the first branch has only one segment, and the second branch considers *n* segments as separate sources. That is, estimated earthquake losses from the *n* individual segments are added together in this branch. Since incomplete branches on the logic tree tend to underestimate seismic hazard and earthquake risk, it is necessary to determine that all branches are complete (Abrahamson, 2000).

2.4 Spatial, temporal and intensity uncertainties

It is necessary to note that characterization of seismic sources and seismogenic zones (epicenter location, occurrence time and seismic intensity) is based on delimitation of type A, type B and type C zones discussed in numeral 2.1. Since it is not possible to predict the times, locations and magnitudes of future events reliably, several approaches have been proposed by different authors, in order to represent the earthquake patterns in a region. This condition recalls that models to characterize seismic sources and/or seismogenic zones are only idealizations of reality. In addition, the earthquake patterns in a region are not stationary, which is clearly explained through the variations of seismicity on the intermediate (years and decades) and long-term (centuries and longer) periods (Kagan and Jackson, 1994). For these reasons, the characterization of seismogenic zones to carry out probabilistic earthquake risk analysis of a given site should consider the uncertainty about the times, locations and magnitudes of future events, which depends markedly on the kind of geological, geodetic and historical information of the seismic source or seismogenic zone under study.

The characterization of seismogenic zones is focused to identify if the available data of observed earthquakes within each one of them adjust to a model where the time of occurrence, the location and intensity are mutually independent. The selection of the appropriate kind of model to characterize the space, size and time uncertainty depends basically on whether the available information allows the complete characterization of individual and well-defined sources, or whether only it is possible to characterize a big region composed by the combination of several seismic sources. In this stage of the seismic hazard assessment, it is important to remark that the approaches to characterize uncertainty in terms of location, time and size are interrelated, which implies that the selected hypothesis and methods to carry out the analysis of one of those variables may lead to specific approaches to evaluate the others. Therefore, the quality and quantity of available data control the applicable hypothesis and methods to characterize the uncertainty associated to epicenter location, earthquake occurrence time and seismic intensity, which are described in Figures 2 to 4.

2.5 Maximum magnitude

The maximum magnitude is thought to be the largest magnitude that can occur on a fault. This is a case where the terminology is misleading. A magnitude is estimated for each seismic source based on the fault dimension (area or length), or fault displacements. There are several relationships between mean magnitude and fault rupture area, which are characterized by significant random variability. The mean magnitude is often mislabeled as the “maximum magnitude”. Equations relating magnitude and fault rupture has a standard deviation of σ magnitude units, because not all earthquakes of a given magnitude have the same rupture area. The true maximum magnitude is the magnitude at which the magnitude distribution is truncated (at n standard deviations above the mean). With fault segmentation, the issue becomes more confused because the maximum magnitude could be based on rupture of a single segment or multiple segments (Abrahamson, 2000).

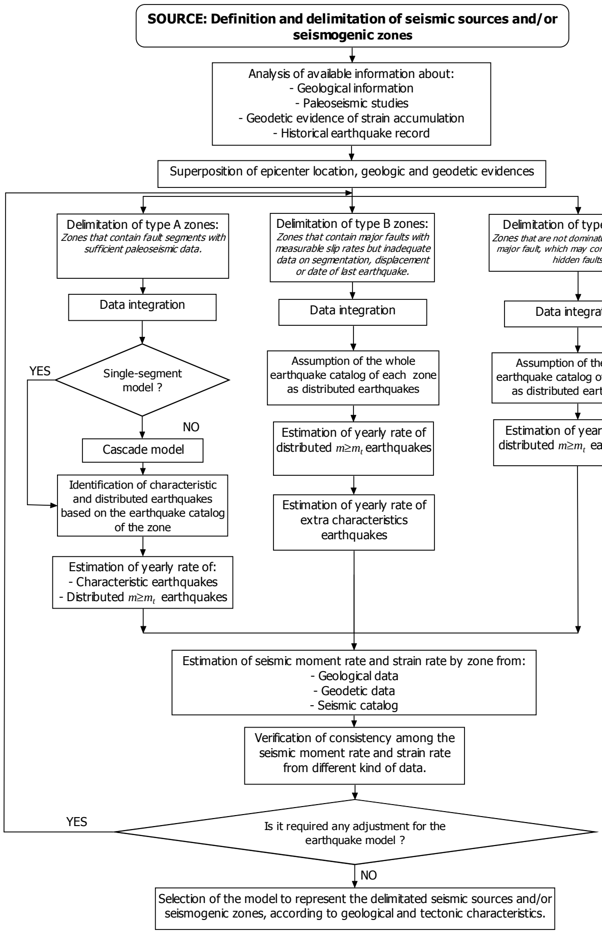

Figure 1. Methodology for definition and delimitation of seismic sources and/or seismogenic zones.

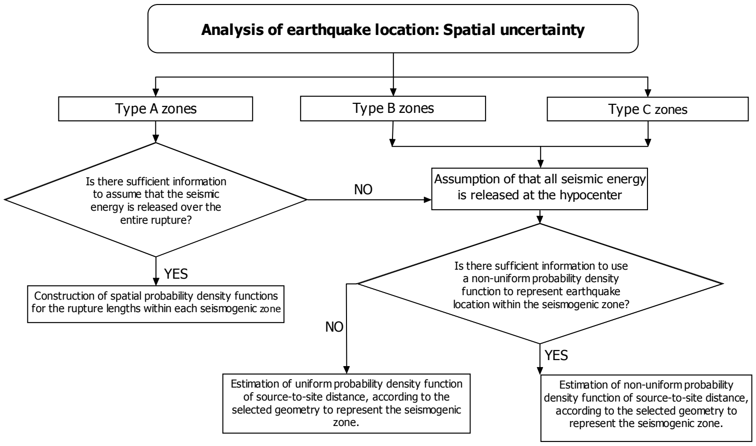

Figure 2. Methodology for the analysis of spatial uncertainty of earthquakes.

2.6 Parameter compatibility of ground motion prediction equations (GMPEs)

The GMPEs use a wide variety of definitions for the basic predictor variables, such as the horizontal component of motion, the magnitude scale, and the measure of source-to-site distance. These have to be properly adjusted in order to combine the corresponding equations in a logic tree. Otherwise, these parameter incompatibilities will result in systematic differences between the ground motion predictions from the individual models and distort the estimate of the total uncertainty. (Scherbaum, F. et al.,2005).

Most modern GMPEs use definitions more reallistic of the source-to-site distance, which reflect the dimensions of the fault rupture for larger earthquakes. Traditional GMPEs use point-source measures relative to the epicenter. In this issue it is necessary clarify that is not correct to neglect differences in distance definitions. The appropriate distance measure should be used with each GMPE considered. However, definition and delimitation of seismic source and/or seismogenic zones for probabilistic seismic hazard and earthquake risk analysis almost invariably include areas of distributed point-source seismicity and linear fault sources. Bommer and Akkar demonstrated the errors that can result from combining point-source simulations and extended-source distance metrics. The simplest and most consistent solution is for all GMPEs to be derived pairs of equations, one using an extended-source distance measure, and another using a point source measure (Bommer, J.J. and Akkar, S., 2012). When several GMPEs are combined in a logic tree for probabilistic seismic hazard and earthquake risk analysis to capture the epistemic uncertainty in predicted median ground motions, adjustments need to be made for compatibility if these equations are based on different distance measures. Such empirical adjustments can lead to severely inflated standard deviations of the adjusted GMPEs, which will exert a strong influence on the results of the probabilistic seismic hazard and earthquake risk analysis (Bommer, J.J. and Akkar, S., 2012).

Incompatibilities in terms of magnitude scale and definition of the horizontal component of motion (larger, random or geometric mean) may be corrected using empirical correlations. Another potential source of incompatibility is when the logic tree contains equations that include a predictor variable that is not used in others (e.g. style-of-faulting), which also may be corrected through a procedure to achieve compatibility among the median values. All procedures applied to treat the various incompatibilities imply an increase in the corresponding aleatory uncertainties in the individual predictions (Bommer, J. et al, 2003).

2.7 Ground motion prediction equations at rock level

The application of GMPEs to quantify attenuation effects is generally recognized to be the major source of uncertainty in seismic hazard estimates, particularly for low annual frequencies of exceedance. In general, GMPEs relate a characteristic parameter of the ground motion in a specific site (e.g. peak ground velocity, peak ground acceleration, response spectral values, and Fourier spectral values) to a representative parameter of the size of the earthquake, generally magnitude. Magnitude, distance and site conditions are the main variables used in GMPEs. Since amplification amplification, liquefaction, lateral spreading and landslide phenomena have shown their marked influence on earthquake losses worldwide (e.g. Japan (2011), New Zealand (2010 and 2011), Haiti (2010), Chile (2010), El Salvador (2001) and Colombia (1999), it is desirable to evaluate attenuation effects through ground prediction equations that estimate ground motion at bedrock level. In this way, it is possible to treat local site effects with a detail approach, according to needs of reducing uncertainties involved in earthquake risk assessment.

2.8 Number of standard deviations for probability model of ground motion

Since GMPEs are probabilistic descriptions of the ground motion, they are characterized by the median ground motion, the standard deviation, and the form of the distribution. Ground motions greater than 1 standard deviation above the median can and do occur. In the current strong ground motion database, there are hundreds of recorded ground motions that exceed one standard deviation above the median. Statistical evaluations of recorded ground motion data indicate that the data begin to deviate from a lognormal distribution 2 standard deviations above the median, indicating that the probability model for ground motion is less reliable from 2 standard deviations above the median (Abrahamson, 2000).

There is no empirical evidence to support truncation of the ground motion at less than 2 standard deviations. Doing so result in an under prediction of the seismic hazard and earthquake risk. The standard deviation itself does not represent statistical uncertainty, but rather it represents randomness in the earthquake source process and wave propagation. As a result, a common practice in probabilistic seismic hazard evaluations is to limit the number of standard deviations to be less than 3 (Abrahamson, 2000).

3. LOCAL SEISMIC HAZARD

3.1 Variability is part of the probabilistic description of the ground motion

It is commonly thought that including the standard deviation is more conservative than using just the median ground motion. It is not more conservative to include the standard deviation in a probabilistic earthquake risk analysis. Using a zero for the standard deviation significantly underestimates the local hazard. The underestimation of the hazard becomes greater at low probabilities (long return periods).

3.2 Requirement of data of representative soil profiles at the site

There are two basic local site effects associated with earthquakes: (i) Earthquake ground motion (amplification effects) and (ii) physical failure of soil profile (e.g.fault rupture, landslide, liquefaction). Some authors have remark the importance of site-specific analysis, through analytical and instrumental data that show the influence of some variables such as thickness of the soil profile, relationships of shear modulus reduction with cyclic shear strain, and bedrock stiffness on earthquake site response (Dobry, R.,1992; Dobry, 1998; Estrada, G.M. 2001). For development of earthquake risk models it is desirable the characterization of earthquake ground response of soil profiles through transfer functions or ratio of response spectra (RRS - based on the response spectra at the soil surface and at the rock level for each structural period). This analysis allows calculation of ground motion as the RRS times the spectrum at rock level. In addition, it results essential to identify soil profiles with potential of liquefaction effects or landslide associated with earthquake.

Influence of amplification effects on earthquake damage has been widely demonstrated and confirmed by recent events, such as the 2010 Chile earthquake, the 2010 Haiti earthquake, and the 1999 Colombia earthquake. The 2011 New Zealand earthquake and its effects in the city of Christchurch, highlighted the potential of damage of widespread liquefaction and lateral spreading. Therefore, earthquake risk models should count on calculus algorithms of earthquake ground response that uses transfer functions or RRS in estimations of earthquake ground motions, as well as definition of those soil profiles with susceptibility to liquefaction or landslide. Several cities have results worldwide of seismic microzonation studies, which establish homogeneous zones with similar earthquake ground response. Specific analysis of local site effects o seismic microzonation studies should be incorporated iin earthquake risk models and link its results with algorithm of damage.

4. SEISMIC VULNERABILITY

Seismic vulnerability of a building can be described by means a function between earthquake intensity and damage. Of major importance in application of methodologies to evaluate seismic vulnerability is not only the development of earthquake risk models with representative vulnerability function of buildings and construction practices at the site, but also the acquisition of comprehensive data of structural and non-structural components, which allow characterization of variables that control seismic performance of buildings. From a methodology point of view, the lack of an adequate database with which to develop accurate damage algorithms is a major constraint, because seismic vulnerability estimation depends markedly on specific characteristics of the structure. Consequently, it is recommended a careful procedure to compile building database for users of earthquake risk models.

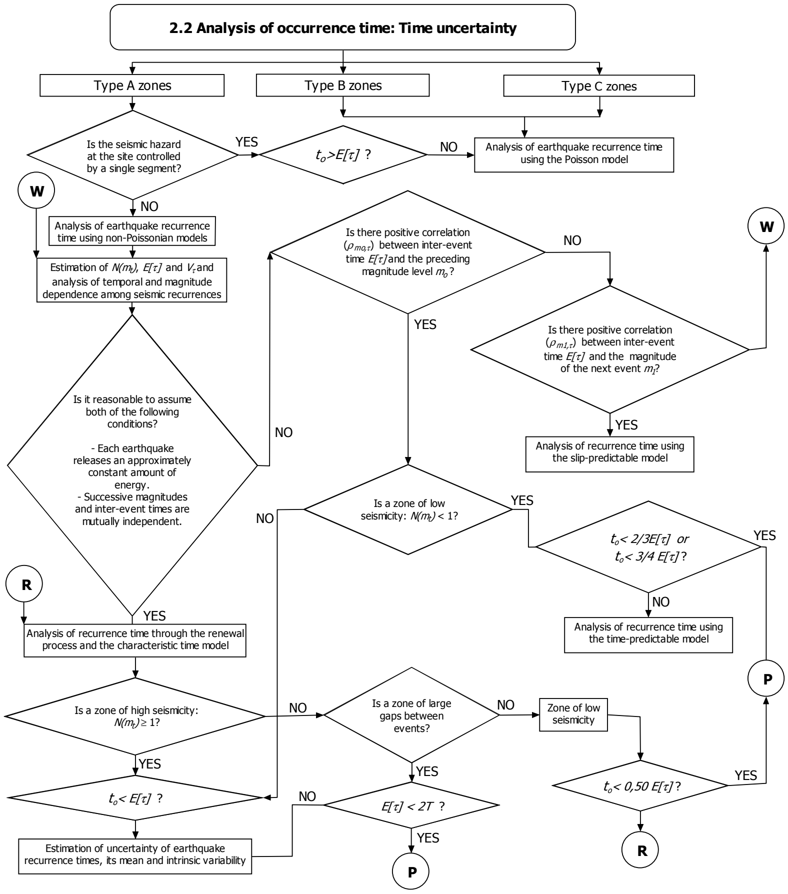

Figure 3. Methodology for the analysis of temporal uncertainty of earthquakes (t_o: time since the last characteristic earthquake; $E[\tau]$: Mean recurrence interval of characteristic earthquakes; T: Earthquake recurrence interval in zones of large gaps between events).

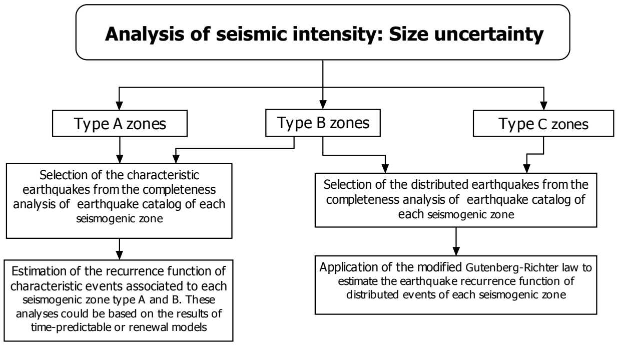

Figure 4. Methodology for the analysis of size uncertainty of earthquakes.

The survey of resulting damage of the 2010 Haiti earthquake demonstrated that the frequency of damage in reinforced concrete buildings was enormous. Based on criteria of cross-sectional areas of building columns and walls, 90% of the structures surveyed in Haiti would have been classified as seismically vulnerable before the earthquake. The 1999 Colombia earthquake caused structural and non-structural damage of unreinforced masonry structures and reinforced concrete buildings. Lessons from the 2010 Chile earthquake showed the great influence of irregularities (e.g. soft story, setbacks) on building damage (Estrada, G.M., Jaramillo, J.D. and Rochel, R., 2010). On the other hand, the 2011 New Zealand earthquake resulted in the collapse of multistory buildings and unreinforced masonry structures in the Christchurch city center. Then, these lessons show that is necessary to count not only with data about type of structure, but also with some decisive details about structural and non-structural configuration of buildings.

5. CONCLUSIONS

The probabilistic approach is the most appropriate to develop earthquake risk models. However, representativeness of its evaluations depends deeply on treatment of aleatory and epistemic uncertainties involved in estimation of regional and local seismic hazard, as well as in characterization of structural vulnerability. Analysis on common practice of earthquake risk assessment and software development to estimate expected losses allowed identification of key issues to handle and reduce overall uncertainties. Some of those key issues are the following: (i) clear knowledge about the scope of the probabilistic approach and the corresponding terminology, (2) definition, delimitation and characterization of seismic sources and/or seismogenic zones according to available data (Type A, B and C zones), (3) treatments to handle parameter compatibility of GMPEs, (4) requirement of representative data of soil profiles that characterize amplification effects, liquefaction and landslide potential associated with earthquake, and (5) compilation of structural and non-structural data that control seismic performance of buildings.

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