Several probabilistic seismic hazard analyses have been performed in most countries of the Latin America and Caribbean (LAC) region during the past 15 years but, most of them have been developed for specific needs of a single country. This work presents a complete, continuous, homogeneous and comprehensive PSHA that includes all the countries where seismic hazard is relevant in LAC region. A homogeneous earthquake catalogue was assembled and based on it, a regionalization of the subduction zone in the Pacific was developed. This data led to the definition of a set of sources which were later complemented by those associated to the intra-plate activity. For the last, since they are associated mostly to the transnational cordilleras, geometrical continuity along the political borders was ensured for all cases. PSHA was performed using CRISIS2015 computer program, a worldwide well-known and accepted tool. The main output of the study are intensity exceedance curves at several locations from where hazard maps for fixed return periods and different spectral ordinates are obtained. The results of this effort besides the academic and scientific remark are very useful for transnational seismic risk assessments where in case of using the existing models the discontinuities in the seismic hazard were to be also reflected in the risk results, mainly for portfolios located either close to the political borders or to portfolios comprising dwellings in more than one neighboring country.

Keywords: Probabilistic seismic hazard analysis; subduction zonation; probabilistic seismic risk assessment; seismicity models; CAPRA.

1. INTRODUCTION

Most countries in the Latin America and the Caribbean region (LAC), since more than 25 years ago, have had probabilistic seismic hazard analyses (PSHA). Anyhow, most of them have been developed only with a national scope and objective and therefore, the estimation of the ground motion intensities has not overstepped the political borders of each individual country. Although those studies are acknowledged to have high quality, have used state-of-the-art approaches at the time of development and, in most cases, have been considered for the definition of the seismic design coefficients in the national earthquake resistant building codes, important discontinuities in the vicinity of the political borders exist due to the lack of integration of transnational faults as well as the use of ground motion prediction models (GMPMs) with different characteristics and parameters. This last aspect has relevance not only in the use and interpretation of the models but on the quantification of seismic risk by means of fully probabilistic (event-based) approaches, such as the one proposed by Ordaz (2000)
and then, its estimation on exposure portfolios that have assets in different neighbouring countries should not be done by simply putting together two seismic hazard models that were developed separately.

This paper presents the approach, methodology, data sources and results used for the development of what is the first harmonized and fully probabilistic seismic hazard model with national resolution level for the LAC region (ASLAC model) which on the other hand, has been developed under the framework of the update for the latest release of ERN’s R-Plus system (ERN, 2016). An earthquake catalogue was assembled (using international, regional and local data sources), followed by a de-clustering process in order to remove fore and aftershocks. The process was complemented by a review of the location and characteristics of specific events for a better assignation in terms of location and magnitude of them. The magnitude recurrence relationships assigned are mostly based on the modified Gutenberg-Richter (G-R) (Cornell and Van Marke, 1969) model but for some subduction sources it was combined with the Youngs and Coppersmith (1985) seismicity model (which uses a G-R relation for low magnitudes and a uniform density function describes the seismicity with the characteristic magnitude for higher values of $M$). A comprehensive review of GMPMs was performed in order to use the ones that better adjust to the seismo-technic characteristics of the region, combined also with models that have been developed using local data. For most of the sources a combination of different models was made by means of hybrid (or composite) GMPMs (Scherbaum et al. 2005).

The ASLAC model has a national resolution level at all locations which on the other hand, allows the performance of detailed seismic risk assessments at any location within it. PSHA is performed on the well-known program CRISIS2015 (Ordaz et al. 2015) and the results are obtained in terms of intensity exceedance probabilities for different timeframes, uniform hazard spectra and maps for different spectral ordinates and mean return periods. Also, a set of stochastic events, suitable for fully probabilistic seismic risk analyses was generated in *.AME format (Torres et al. 2014; Quijano et al. 2015).

This is the first harmonized, continuous and fully probabilistic seismic hazard model that has been developed for the whole LAC region with the above mentioned resolution level and constitutes an important contribution to the regional earthquake engineering field. The development of this new model not only provided the opportunity of using a common approach and methodology in the region but also the chance of using the most updated and openly available datasets in terms of earthquake catalogues and tectonic zonations.

2. TECTONIC AND SEISMICITY DATA

2.1 ASLAC catalogue

The catalogue assembled for the ASLAC model considered mainly data from international sources (Engdahl and Villaseñor, 2002; Storchak et al. 2013; USGS-NEIC, 2015) which was later complemented and reviewed with regional and national information. A threshold magnitude, $M_0$, equal to 4.0 was selected and a de-clustering process was used in order to include only the main-shocks. The first event in the ASLAC catalogue dates back to October 29th 1900 and the cut-off was made in December 31st 2015. Studies for specific events were also used for validation and verification purposes (Singh et al. 2011) and some historical earthquakes included in the ISC-GEM catalogue (v3.0), mostly in Mexico, were relocated. In order to have all events in the catalogue reported in the same type of magnitude, for those in magnitudes different than $M_W$ the global relationships proposed by Scordilis (2006) for $M_S$ and $mb$ were used. A total of 56,953 events remained in the final version of the ASLAC catalogue and the largest reported magnitude corresponds to a 9.6 event in Chile.

Earthquakes in the catalogue are classified into two broad categories: subduction and crustal. The first one groups interface, intraslab and outer-rise events whereas the second one groups the intraplate and shallow seismicity. Figure 1 shows the relative share of the events assigned to each of these four
Figure 1. Distribution of events in the ASLAC catalogue by category

Also, a completeness verification process following the procedure proposed by Tinti and Mulargia (1985) was developed for different $M_o$'s (4.0, 4.5, 5.5, 6.5, 7.5 and 8.0) but, since the geographical extension of the area under study is large, this verification was done by sub-regions as listed next. Table 1 shows the completeness timeframes for the different $M_o$'s considered.

- Mexico and Central America
- The Caribbean
- South America N (Venezuela, Colombia, Ecuador and Peru)
- South America S (Chile and Argentina)

<table>
<thead>
<tr>
<th>Region</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>Mexico and Central America</td>
<td>1972</td>
</tr>
<tr>
<td>The Caribbean</td>
<td>1972</td>
</tr>
<tr>
<td>South America (N)</td>
<td>1971</td>
</tr>
<tr>
<td>South America (S)</td>
<td>1972</td>
</tr>
</tbody>
</table>

2.2 Tectonic zonation

The tectonic zonation process for the ASLAC model required the definition of detailed sources in order to guarantee the national level resolution of it. First, a classification into subduction (considering both interface and intraslab) and crustal activity was made followed by the definition of individual sources. In all cases, the zonations were based solely on the characteristics of the seismo-tectonic environment ignoring in all cases the political borders and, therefore, having continuity along the area of analysis. For the subduction zonation, cross sections every 2º were obtained using the Slab v1.0 (Hayes et al. 2012) datasets, whereas for the crustal zonation, previously published national and regional studies were used, like for example (OSC, 1983; Tavera, 2014; Salgado-Gálvez et al. 2016). Since there were different criterions applied along the area of analysis, an explanation of the zonation performed for the different regions is included herein.

2.2.1 South America

Seismic activity in South America was classified using the following criterion:

- All events which epicentres are located between the subduction trench and the 50km contour level are considered as interface.
- All events outside the 50km contour level are classified as:
Intraslab if $H \geq d - (30 + 0.15d)$, where $H$ is the event’s depth and $d$ is the interface depth.

Crustal if the last criteria does not apply

With the seismic activity differentiated into these three main categories, the different seismogenetic sources were defined after identifying zones with similar seismic activity. The work developed by PMA (2008) was also used to identify the different individual fault traces in the Andean region that crosses national borders in order to group them by families and then define continuous sources.

**2.2.2 Mexico and Central America**

Since the subduction zone in this region has some peculiarities, the criterion for the classification of the seismic activity had slight changes between Mexico and Central America. On the one hand, for Mexico the criterion was:

- All events which epicenters are located between the subduction trench and the 50 km contour level are considered as interface.
- All events outside the 50 km contour level are classified as:
  - Intraslab if the depth of the event is higher than 50 km
  - Crustal if the depth of the event is lower or equal to 50 km.

On the other hand, for Central America the criterion was:

- All events which epicenters are located between the subduction trench and the 40 km contour level are considered as interface.
- All events outside the 40 km contour level are classified as:
  - Intraslab if the depth of the event is higher than 40 km
  - Crustal if the depth of the event is lower or equal to 40 km.

Additionally, the events located up to 100 km to the west of the subduction trench were classified as outer-rise. In this region, since for Central America (Belize, Guatemala, Honduras, El Salvador, Costa Rica, Panama and Nicaragua), a detailed and national resolution level tectonic zonation was developed under the framework of the RESIS II project (Benito et al. 2012) and also a detailed zonation was previously done in Mexico (Pérez-Rocha and Ordaz, 2008), the geometry of the crustal sources proposed in those two studies was used only with some minor changes.

**2.2.3 The Caribbean**

The geometry of the seismic sources in the Western Caribbean was defined after the study of Salazar et al. (2013) covering territories of Jamaica, Cuba, Haiti and other smaller surrounding islands. For the Dominican Republic, the zonation stage considered previous studies. The seismogenetic sources considered for the Eastern Caribbean in the ASLAC model are based on the work of Bozzoni et al. (2011) which extends from Puerto Rico, southwards to Venezuela in the vicinity of Trinidad and Tobago.

Seismicity in the Caribbean was first divided into shallow and deep activity. In the first classification, events with less than 50 km were included and the remaining ones were left in the second classification. According to the characteristics of the sources, using the description of Bozzoni et al. (2011) and Salazar et al. (2013), events were assigned to individual crustal or subduction sources.

Figure 2 shows the crustal sources (left) and the subduction sources (right) included in the ASLAC model.
2.3 Seismicity models and parameters

A Poissonian earthquake occurrence process has adopted for the ASLAC model and, depending on the seismicity patterns either the modified G-R model by itself or, a combination between it and the characteristic earthquake (CE) model was used for the estimation of the future seismic activity at each source. Depending on the seismicity model used in each source a set of parameters are needed for the definition of the magnitude-recurrence relationships. Seismicity, when described by means of the G-R model, follows the following magnitude recurrence relationship:

\[
\lambda(M) = \lambda_0 \exp(-\beta M) / \exp(-\beta M_U)
\]

where \(\lambda_0\) is the exceedance rate of the threshold magnitude, \(M_0\); \(\beta\) is a parameter equivalent to the "b-value" for the source (except that it is given in terms of its natural logarithm) and \(M_U\) is the maximum magnitude for the source. \(\lambda_0\) and \(\beta\) \((a\) and \(b)\) parameters were calculated using a maximum likelihood methodology. For the cases where the Youngs and Coppersmith seismicity model was used, the G-R relation was used between \(M_0\) and \(M_U^{GR}\) and from that value onwards, the CE model, which follows the following magnitude recurrence relationship, was used. For the second part, seismicity is described by means of:

\[
\lambda(M) = \lambda_{ych} \Phi\left(\frac{M_U - EM}{s}\right) - \Phi\left(\frac{M - EM}{s}\right)
\]

where \(\Phi[\cdot]\) is the standard normal cumulative function, \(M_U\) and \(M_U^{GB}\) are the minimum and maximum characteristic magnitudes respectively, and \(EM\) and \(s\) are parameters defining the distribution of \(M\). \(EM\) can be interpreted as the expected value of the characteristic earthquake and \(s\) as its standard deviation. \(\lambda_{ych}\) is the exceedance rate of magnitude \(M_0\). In those cases it was combined with the G-R model as schematically shown in Figure 3.
For all sources, $M_U$ was defined by means of geological studies [19], previous PSHA, expert criteria and historical data. Figure 4 shows the $M_U$ values used for the crustal and subduction sources in the ASLAC model.

3. GROUND MOTION PREDICTION MODELS

Different GMPMs were used depending on the tectonic environment of each seismic source (i.e. subduction, crustal, type) and also on the availability of GMPMs developed using data of the LAC region. As in the case of the tectonic zonation a classification into subduction and crustal categories was made, bearing in mind that in the first one, interface and intraslab activity is grouped. Since the output of the model is to be used in probabilistic seismic risk analyses which are usually performed on portfolios that have assets with different characteristics, only GMPMs that cover, at least, the 0.0-5.0s range were considered. The criterion for selecting GMPMs proposed by Cotton et al. (2006) was used, together with specific studies developed for the recommendation and assignation of GMPMs in the
region (Arango et al. 2012). Zhao et al. (2006) and Chiou and Youngs (2014) GMPMs were initially assigned to the subduction and crustal sources respectively, and then for each country, those models were combined in order to use hybrid (composite) GMPMs.

A hybrid GMPM is the result of the weighted combination of two or more models that have different mean values, standard deviations or both. Therefore, the conditional probability of exceeding an intensity measure $A$ is calculated by means of:

$$P(A > a) = \sum_{i=1}^{N} w_i \left(1 - \Phi \frac{a - \mu_i}{\sigma_i}\right)$$ (3)

where $w_i$ is the weight assigned to the $i^{th}$ base GMPM, $\Phi$ is the normal distribution and $\mu_i$ and $\sigma_i$ are the mean values and standard deviations respectively of the $i^{th}$ base GMPM.

Table 3 shows the base models used for the hybrid GMPMs used at different regions and countries for crustal, subduction and outer-rise sources. Some GMPMs, such as Zhao et al. (2006) have specific options for interface, intraslab and crustal activity; others like (Chiou and Youngs, 2014) are defined for different types of fault (i.e. normal, strike-slip, etc.) and therefore, depending on the characteristics of each source, the most appropriate option was selected. For all cases, GMPMs intensities are estimated at bedrock level since the local site effects are to be considered when performing seismic risk analyses by means of spectral transfer functions defined at specific locations.

Table 2. GMPMs used by region and tectonic environment

<table>
<thead>
<tr>
<th>Region/Country</th>
<th>Seismicity classification</th>
<th>Base GMPMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mexico</td>
<td>Crustal</td>
<td>Chiou-Youngs (2014) - Abrahamson et al. (2014)</td>
</tr>
<tr>
<td></td>
<td>Interface</td>
<td>Zhao et al. (2006) - Arroyo et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Intraslab</td>
<td>Zhao et al. (2006) - García et al. (2005)</td>
</tr>
<tr>
<td>Central America</td>
<td>Crustal</td>
<td>Chiou-Youngs (2014) - Climent et al. (1994)</td>
</tr>
<tr>
<td></td>
<td>Outer-rise</td>
<td>Chiou-Youngs (2014)</td>
</tr>
<tr>
<td>Colombia, Ecuador</td>
<td>Interface</td>
<td>Zhao et al. (2006) - Bernal (2014)</td>
</tr>
<tr>
<td>Trinidad and Tobago</td>
<td>Crustal</td>
<td>Campbell and Bozorgnia (2014) - Abrahamson et al. (2014) - Zhao et al. (2006) - Boore et al. (2014)</td>
</tr>
<tr>
<td>Colombia, Ecuador, Peru, Bolivia, Chile, Argentina</td>
<td>Intraslab</td>
<td>Zhao et al. (2006)</td>
</tr>
<tr>
<td>Peru, Bolivia, Chile, Argentina</td>
<td>Crustal</td>
<td>Chiou-Youngs (2014)</td>
</tr>
</tbody>
</table>

4. METHODOLOGY

For the estimation of the seismic hazard it is assumed that the intensities, in this case spectral accelerations ($S_a$), are random variables that follow a log-normal distribution. Therefore, the probability that a certain intensity level is exceeded as a result of an event with known magnitude and distance, $\Pr(A > a|M, R)$, can be calculated as:
\[ \Pr(A > a | M, R_i) = \Phi\left[ \frac{1}{\sigma_{Lna}} \ln \frac{\text{MED}(A | M, R_i)}{a} \right] \]  

(4)

where \( \Phi[\cdot] \) is the normal standard distribution, \( \text{MED}(A | M, R_i) \) is the acceleration median given by the GMPM which at the same time is associated to a known magnitude-distance pair and \( \sigma_{Lna} \) is the standard deviation of the natural logarithm of the acceleration that accounts for its uncertainty. When area and area planes geometrical models are used, the geometries of the sources are subdivided into triangles. With this, the location of the simulated earthquakes is determined by the gravity center of each of them and therefore, a spatial integration process that considers these different locations is needed. The spatial occurrence probability of future earthquakes is assumed as uniform along each source, which in other words means that every gravity center has the same probability of being an epicenter. The intensity exceedance rate at any location for each seismic source is calculated as:

\[ v_i(a) = \sum_j w_{ij} \int_{R_{ij}}^{M_i} \left( -\frac{d\lambda(M)}{dM} \right) \cdot \Pr(A > a | M, R_{ij}) \cdot dM \]  

(5)

where \( j \) corresponds to the number of triangles into which the seismic source has been subdivided into, \( w_{ij} \) is the weight of each triangle which is proportional to its area, \( R_{ij} \) is the distance between the occurrence site and the \( j^{th} \) element of the \( i^{th} \) source and \( \Pr(A > a | M, R_{ij}) \) is the probability that the acceleration is exceeded given the occurrence of an earthquake with magnitude \( M \) at \( R_{ij} \) distance. Finally, since there is usually more than one seismic source that can contribute to the acceleration exceedance rate at each computation site, the contribution of each individual source is added by means of:

\[ v(a) = \sum_{i=1}^{N} v_i(a) \]  

(6)

5. RESULTS

The outputs of interest of this PSHA are classified in two categories:

1. Intensity exceedance rates and/or probabilities
2. Stochastic event set

In the first category are included the hazard curves and uniform hazard spectra (UHS) that can be obtained for any location within the analysis area as shown for some selected cities in Figures 5 and 6. Annual exceedance probabilities are shown for peak ground acceleration (PGA) whereas the UHS are shown for 225, 475, 975 and 2,475 years mean return period. From the hazard curves obtained at every computation site, seismic hazard maps can also be developed as the ones shown in Figure 7 for PGA and 475 years mean return period and 0.5s and 2,475 years mean return period.
Figure 5. Annual exceedance probability plots for selected cities

Figure 6. Uniform hazard spectra for different mean return periods for selected cities
The second output category corresponds to a set of stochastic events that are mutually exclusive, collectively exhaustive and that have a probabilistic representation through the consideration of the first two probability moments for the hazard intensity ($S_a$), together with an annual occurrence frequency. Events (and their associated intensities and occurrence frequencies) are stored in *.AME format which is a convenient file for fully probabilistic risk assessments and compatible with several open and proprietary risk assessment modules. More than 450,000 events are included in the final stochastic set.

6. CONCLUSIONS AND DISCUSSION OF THE RESULTS

The ASLAC model constitutes a multidisciplinary and comprehensive effort in the task of increasing seismic hazard and seismic safety information for the LAC region. This is, to date, the first continuous and harmonized PSHA with a good enough resolution level at all locations to perform detailed fully probabilistic seismic risk analyses which captures the different seismo-tectonic characteristics and provides reliable results for any site inside the area under study accounting also for the uncertainties in the different components of the PSHA.

The ASLAC model captures well the seismicity activity patterns at different locations not only in terms of occurrence but of rupture characteristics. Its representation was made possible by the use of different approaches that, due to the flexibility of the CRISIS program. Regarding the PSHA tool, even if it is well-known that for the estimation of seismic design coefficients in the LAC region included in the earthquake resistant building codes different versions of the CRISIS software have been used, the ASLAC model also positions the tool as the pioneering and widely used one in the LAC region.

Having used a uniform approach, coherent GMPMs according to the tectonic environment and input data at all locations decreases the strongly marked discontinuities at the national borders and this is an issue of high importance in the use of the seismic hazard results in subsequent seismic risk analyses. Nevertheless, it is important to recognize the relevance of the existence of previous national and
regional PSHA which not only served as benchmarks but as valuable information sources for this new model. Results compare well with previous studies at all locations where previous national and regional studies were available and also, as can be clearly seen from Figure 7, the problem of discontinuities in the vicinity of the political borders is solved at all locations.

This new model constitutes an important scientific and technical contribution to a better understanding of the seismic hazard in the region providing valuable information for disaster risk management activities while at the same time using advanced, transparent and high quality tools for the promotion of a seismic safety, prevention and mitigation culture in the LAC region.

7. REFERENCES


