PROBABILISTIC SEISMIC HAZARD ASSESSMENT FOR SOUTHERN PERU

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An evaluation of seismic hazard was performed for Southern Peru region, by using the probabilistic method (PSHA), which takes in consideration uncertainties in the dimension, location, time of occurrence of earthquakes. In this work were used available seismic catalogues and attenuation relationships for that region, in a systematic way of analysis. The level of seismicity in that region is very high in the seismicity context of the Peruvian territory, and in South America, as shown in this work. The interest for this study is because in that region there are large cities, in the order of a million people or more, like Arequipa, Puno, Moquegua, Ilo and Tacna; also because there are large engineering ventures like hydroelectric, and important mines. The main objective of this work is to determine the seismic hazard for some points of interest such as large cities and for selected engineering ventures, by finding the maximum horizontal acceleration that may be provoked by future earthquakes.

For compiling a reliable catalogue were used data of several catalogues such as EHB, ISC, CERESIS and NEIC catalogues, being the EHB and ISC the most important for this work. It was also used data from historical earthquakes compiled by Silgado (1978)[1] and Silgado & Giesecke (1981)[2]. Our compiled catalogue covers the time interval from 1471 till 2012. However, hypocentres obtained with instrumental data from EHB and ISC catalogue since 1960 till 2010, were utilized to evaluate the geometry of the subduction zone between the Nazca and South American plates in this region, which permitted to identify shallow, intermediate and deep earthquakes for this study.

In **Figure 1a** shows shallow earthquake with depth less than *70 km*. These earthquakes are mainly distributed between the trench and the coastline, associated with the subduction process. There is also surface localized seismicity in the continental portion, outside the subduction zone; these earthquakes can be related to surface tectonic deformation.

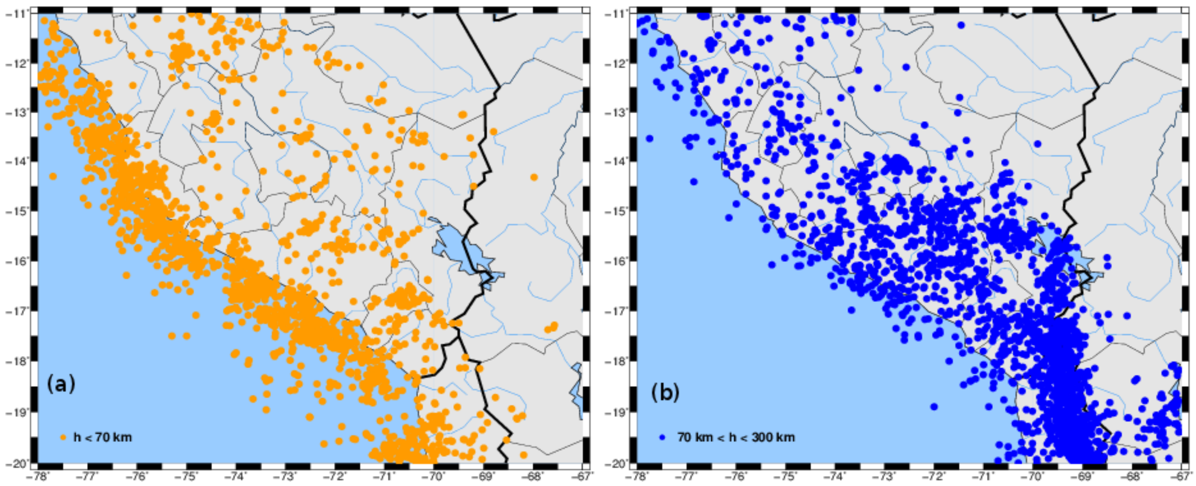

Figure 1. Region of interest showing earthquakes with shallow and intermediary focus, occurred from 1960 to 2010 with mb ≥ 3.0 compiled in EHB and ISC catalogues. **(a)** Depth of $h \leq 70\ km$ and **(b)** depth of $70\ km < h \leq 300\ km$.

In **Figure 1b** shows the distribution of earthquakes with intermediate focus, *70 km< h < 300 km*, these earthquakes are distributed from the coastline toward the continental interior, following the subduction zone, there are larger concentration of earthquakes in Tacna, Moquegua, Arequipa and Apurimac, and part of Cuzco, Puno and Ayacucho states. This figure also shows a lower concentration of earthquakes for the portion located further north of latitude 13^{o}S.

Deep focus earthquakes, *h > 300 km*, are shown in **Figure 2a**, showing those earthquakes are distributed mostly in the eastern region of Peru, focused on the Peru-Brazil border following a N-S alignment and on the Peru-Bolivia border (between 13 ° and 16 ° S) in a dispersed manner.

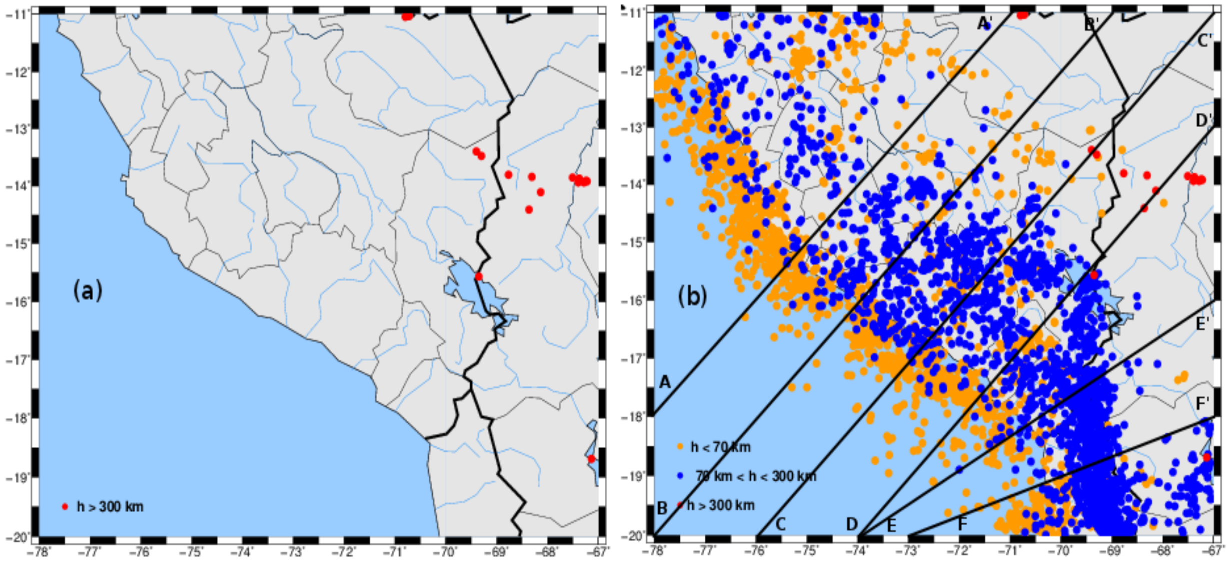

Figure 2. (a) Study region showing earthquakes with deep focus, occurred from 1960 to 2010 with *mb* ≥ 3.0 compiled in EHB and ISC catalogues to depth of *h* ≥ *300 km* and **(b)** showing locations of sections to plot hypocentres earthquakes to evaluate subduction zone and seismogenic sources.

To identify the seismogenic sources in the region of study is necessary to make some seismic sections perpendicular to the coastline of the Peru. Through this analysis of those sections is possible to define the subduction geometry in southern Peru, for defining the seismogenic sources types necessary to for PSHA study.

For elaborating the seismic section the hypocentres were projected to the vertical plane passing for each line considering all earthquakes located up to *80 km* on both sides on the line. **Figure 2b** shows the lines drawn for each section. **Figure 3** shows the projected hypocentres earthquakes on the plane for each section: AA', BB', CC', DD', EE' and FF'. From these figures shoes clearly the Nazca plate subduction process.

From the profiles shown in **Figure 3**, we can define three types of seismogenic sources: two sources in the subduction zone, one down to depth of *100 km*, formed buy inverse faults, and the second source corresponding to the remaining subduction zone up to *300 km*; the third zone corresponds to continental shallow earthquakes, located outside of the coastline.

For each seismogenic sources must be determined the recurrence seismicity curve, by using the Richter-Gutenberg frequency/magnitude relationship[4], the maximum credible earthquake has to be and must be selected a proper attenuation relationship to calculate the hazard curve for given places of interest in Southern Peru, by using the methodology recommended by Budnitz *et al.* (1997)[5].

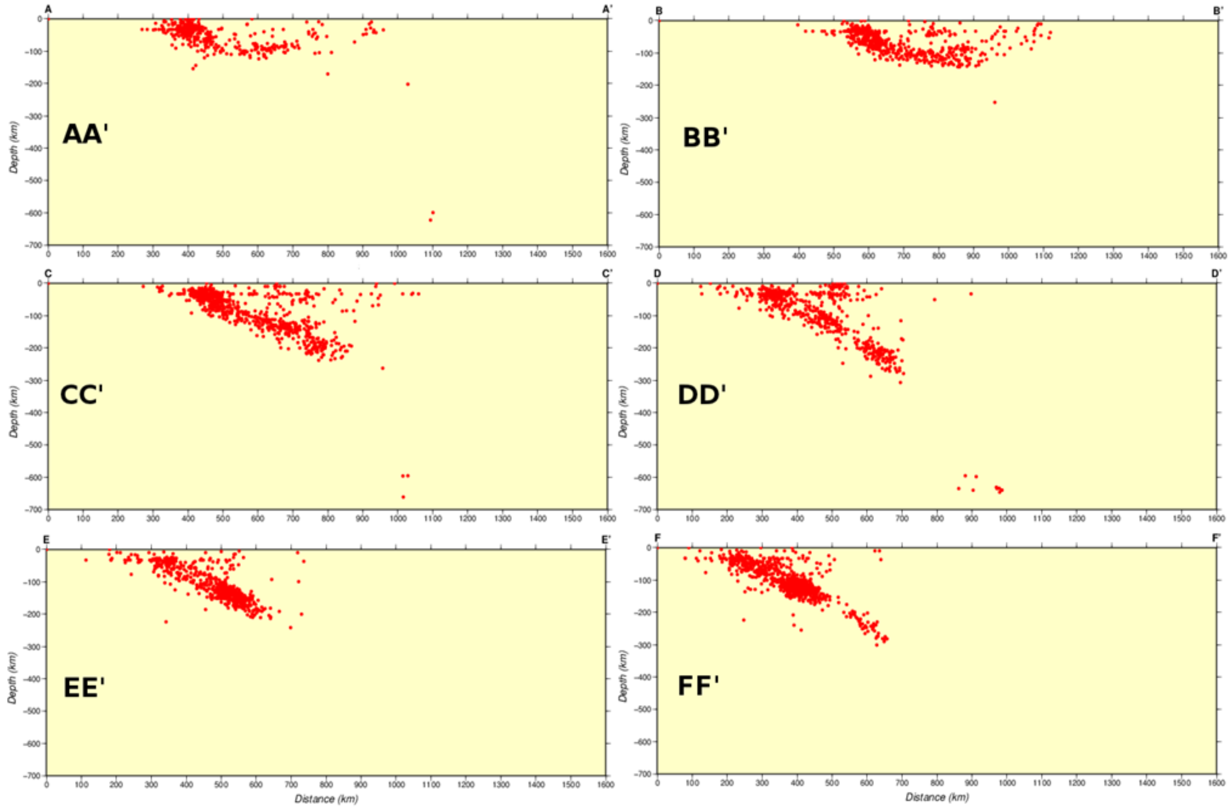

Figure 3. Projection of earthquakes for each section defined in Figure 2b until a depth of *700 km*.

Once the seismic sources and the recurrence seismicity are defined and characterized, follow the calculation of contribution fraction of all events in the probability of exceeding a y^* value of maximum ground acceleration, given by:

$$P_H(y^*) = P\left[Y > y^* \text{in } \ t \text{ years}\right] = 1 - \exp\left(\sum_{i=1}^{n_s}\sum_{k=1}^{N_M}\sum_{l=1}^{N_R} - t \cdot \nu_i \cdot P\left[Y > y^* \mid m_k, r_l\right] p_R(r_l) p_M(m_k)\right) \quad (1)$$

where, N_M is the number of magnitudes within the considered range, N_R is the number of epicentral distances in relation to the site of interest, $p_M(m_k)$ is the probability of M random variable to adopting the m_k value, $p_R(r_1)$ is the probability of R random variable to adopting the r_1 value, i is the considered i-th source, ν_i is the annual frequency for each source of events with magnitudes $\geq m_0$, r_1 distance in kilometres from the site to source, m_k magnitude contained in the interval $[m_0 - m_{max}]$. The peak ground horizontal accelerartion, y^*, is given by:

$$y_r^* = \left(\frac{Ln\ (y^*) - \overline{Ln\ (Y)}}{\sigma_{LnY}}\right) \quad (2)$$

where, $y_r{*}$ is reduced peak ground horizontal acceleration; σ_{LnY} standard error, $\overline{Ln(Y)}$ mean value of the ground peak acceleration distribution.

For subduction region we are using Youngs (1997) attenuation relationship [6], given by:

$$\ln(y) = 0.2418 + 1.414M + C_1 + C_2(10 - M)^3 + C_3 \ln\left(R_{rup} + C_M\right) + 0.00607H + 0.3846Z_r \quad (3)$$

$$C_M = 1.7818\exp(0.554M)$$

$$\sigma_{LnY} = C_4 + C_5M$$

where, y is spectral acceleration in g, $ln(y)$ is ground peak acceleration distribution, M is moment magnitude, R_{rup} is closest distance from site to rupture surface in km, H is depth in km, and $Z_r = 0$ for interface events (such as the Cascadia Zone[7]) and $Z_r = 1$ for intra-slab events (such as the Juan de Fuca[8]). Values for PGA of the coefficients for rock are: $C_1 = 0$, $C_2 = 0$, $C_3 = -2.552$, $C_4 = 1.45$ and $C_5 = -0.1$.

The procedure algorithm developed in this work to compute seismic hazard curves is [9]:

- Discretized seismogenic sources: plane discretization following the subduction source and volumetric discretization for continental seismic source distribution.
- Define temporal distribution of earthquake recurrence relationship for each seismogenic sources.
- Define target peak acceleration level will be exceeded, g^*.
- For each magnitude, m_k, between a lower bound m_l and upper bound m_u contained in the interval $[m_0 – m_{max}]$, do the loop:
  - Compute the probability, p_M $(m_l < m_k < m_u)$, that the magnitude would fall within that interval.
  - For each cell, do the loop:
    - Compute the probability, p_R $(R = r_l)$, where r_l is the distance from site to centre of the cell.
    - Compute the standard normal variable, eq. (2), for m_k, g^* and r_l.
    - Compute the probability, P_H, eq. (1), that the peak acceleration is greater than g^*, using cumulative distribution function.
    - Sum P_H for all cells.
- Finally sum P_H for each m_k.

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