# SEISMIC RISK ASSESSMENT IN PERU

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## Abstract

A seismic hazard analysis developed during 2011-2013 by the Geophysical Institute of Peru and supported by the World Bank for Peru is presented. Event information updated until 2010 was used. Based on this information 33 seismic sources were defined, including areas beyond the borders with Chile, Ecuador and Brazil. Several ground motion prediction equations (GMPE) applicable to the region were analyzed and tested, after which two of them were selected based on their better observed performance.

The seismic hazard model results confirm the great influence of the seismic activity in the subduction zone; however, it is interesting to note fairly high intensities near Moyobamba (San Martin Department) related to shallow activity.

The accelerations on the central coast (near Lima) for a return period of 475 years were found to be 0.45g, higher than those established by the current seismic design standard E.030 (0.40g), which is currently under review. The highest intensities are found on the South coast; for example, in the city of Ica (affected by the August 2007 earthquake) the intensity for a 475 return period is 0.47g, while in the Northern coast intensities are 0.41g. The points within the continent show lower intensity as one moves away from the subduction zone, reaching intensity values as low as 0.08g in Puerto Maldonado, capital of Madre de Dios Region, near the confluence of the borders of Peru, Bolivia and Brazil.

The information generated in this analysis should be complemented by local effects studies conducted in several cities (Lima, Arequipa, Ica and Moquegua) to obtain design intensities in all types of soil.

The current seismic zoning of Peru (Standard E.030) considers three areas with different design intensities. The proposed new standard E.030 considers four areas, splitting the current zone I (zone of lower intensity) into two new zones. The intensity proposed in the new version of the E.030 standard is 0.45g for the entire coast, value that reasonably agrees with the results of this study.

It is expected that this study will be used as a reference for all future infrastructure projects carried out in Peru.

*Keywords: Seismic hazard; seismicity; spectral accelerations; design spectra; attenuation relationships.*

## 1.- Introduction

Peru is located in the most seismically active region in the world and therefore it is necessary to know the likely behavior of this hazard in a given area. In Peru, seismic hazard studies were initiated by Casaverde and Vargas (1980), the work done by Castillo and Alva (1993) with data from the global seismic network and CERESIS for the period 1900-1991, which had greater application in engineering studies and Earthquake Resistant Design Standard in Peru (Standard E030). Further studies were done by Bolaños and Monroy (2004) and Gamarra and Aguilar (2009), both considering seismic data for most recent events., All these works use laws of attenuation of acceleration from primarily US (McGuire, 1974), in addition to those proposed by Casaverde and Vargas (1980) using data from earthquakes and registered in Peru. In general, the use of different databases and attenuation relationships, have allowed many acceleration values for the same point of interest.

In this study, the seismic hazard for Peru is calculated using seismic data for the period 1960 - 2012 from the unification of three catalogs, the one of the Geophysical Institute of Peru, from the Engdahl and Villaseñor (2002) and from the United States Geological Survey (USGS). The probabilistic seismic hazard is estimated according to Esteva (1968) and Cornell (1968) using the computer program CRISIS-2007, developed and updated by Ordaz et al (2007). For this purpose it has been considered the following tasks:

- Update and standardize the basis of seismic data, mainly the magnitude and focus depth.
- Propose new seismic sources with geometries according to the shape of subduction and crustal deformation.
- Evaluate the attenuation relationships (GMPEs) available.
- Make use of the algorithm CRISIS-2007
- Validate the results with the development of response spectra of earthquakes in the last 10 years.

The results obtained in this study represent a contribution to the development of Engineering and Earthquake Resistant Design Code in Peru (Standard E-030).

## 2.- Seismotectonic Features

The characteristics of the main structural elements involved in the process of regional and local deformation in Peru are described below:

**Subduction:** Present on the western edge of Peru and is caused by the convergence of the Nazca plates (ocean) and American plate (continental). The characteristics of this process have been extensively described by Cahill y Isacks (1992), Tavera y Buforn (2001), Bernal y Tavera (2003).

**Nazca plate:** Its geometry is heterogeneous, subhorizontal in the northern and central regions of Peru and normal in the southern region. On the surface, the plate holds the Dorsales Nazca, Sarmiento and Alvarado, and fractures Mendaña, Nazca and Viru; in addition to depressions of Trujillo and Peru-Chile trench.

**Nazca Ridge:** Submerged mountainous structure on the ocean floor and located at the height of latitude 15° with a NE-SW orientation. Its main axis is perpendicular to the coastline close to the city of Nazca.

**Bibs and Alvarado Sarmiento:** Both are facing the Piura department with a NE direction and approximate length of 400 km with parallel axes.

**Mendaña fracture:** Located in the west end of Peru, 11° latitude with NO orientation perpendicular to the pit. Its origin is associated with an old area of divergence of plates (Yamano y Uyeda, 1990).

**Nazca fracture:** Located in front of the Region of Arequipa (South of Peru), the most remarkable bathymetric feature, along with fracture Mendaña. The fracture is aligned NE-SW direction perpendicular to the pit affecting heights of about 700 m above the surface and depths of up to 300 meters (Robinson et al, 2006).

**Viru fracture:** It is located 100 km north of the fracture Mendaña and corresponds to a reverse fault oriented N15 ° E (Krabbenhoft et al 2004).

**Trujillo Depression:** Structure of approximately 5 km wide at its top and over 500 meters at the bottom. This depression has an extension of 270 km long structure.

**Peru-Chile Trench:** Physiographic feature that indicates the start of subduction, with a length of 5000 km from Colombia to Tierra del Fuego in Chile. The pit follows an orientation parallel to the coast with depths up to 6 km and distances from the pit between 80 and 150 km.

**South American plate:** Over time, the process of subduction has modified the morphology of Peru allowing crustal thickening and folding of sediments to give rise to the formation of systems in surface as geological faults. The Andes is the main result of this deformation, it extends parallel to the coast from Venezuela to Chile with widths ranging from 250 km in the central region up to 500 km in the southern region of Peru.

**Seismogenic zone:** In Peru, the largest earthquakes originate at the surface of friction between the Nazca and South American plates produce rupture areas involving smaller segments proportional to the amount of energy released. Seismogenic zones can be divided into three main areas:

- Seismic upper limit: It gives rise to earthquakes of small magnitude.
- Seismogenic zone: Surface on which direct contact between the plates occurs.
- Seismic lower limit: surface below the seismogenic zone characterized by the decrease in the number of earthquakes.

**Tectonics:** Seismicity in Peru has its origins in the interaction of the Nazca and South American plates, and the realignments in the continent as a result of that process. The Andes is the largest unit of he zone, and runs from Colombia to Chile, parallel to the coast line with variable widths and heights. This unit houses the most important volcanic chains of the continent. The second source of earthquakes are geological faults, formed as a side effect of the collision of plates that produce fractures and folds in the earth's crust. In Peru, the main fault systems is found in the Altiplano, area at the foot of snowy mountain with limits of the Western Cordillera and coastal zone.

## 3.- Seismicity in Peru

Seismicity in Peru is due to the subduction process and the dynamics of each of the tectonic units present in the interior of the continent. In Fig 1 the map of seismic activity occurred in Peru from 1960 to 2012 (Mw> 4.0) is presented. Earthquakes hypocenters are identified by their depth as shallow focal depth (h <60 km), intermediate (61 <h <350 km) and deep (h> 351 km). Shallow focus earthquakes are distributed between the line of the Peruvian-Chilean trench and the coast, from Tumbes to Tacna department (red circles) and define the main seismogenic source in the country. Intermediate earthquakes or intraplate focus are divided into three well defined sectors (green circles), the first parallel to the coast below 8° latitude south, the second on the sub-Andean area northeast of the northern region and the last, on the entire southern region of Peru. Deep-focus earthquakes (blue circles), are, as a whole, aligned from south to north, on the border with Brazil and Peru in the East-West on the border of Peru and Bolivia.

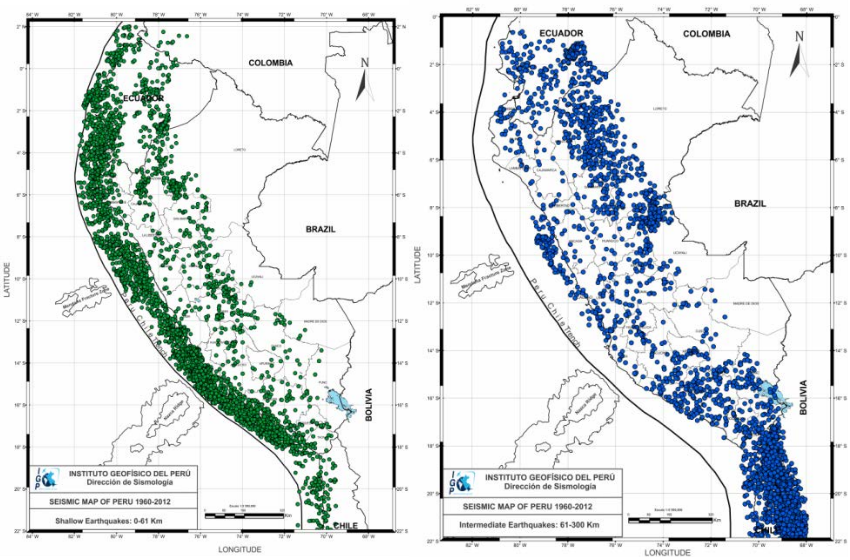


Fig. 1 – Seismicity map for Peru, period 1960 to 2012

### 3.1.- Historical seismicity

Consider information on major earthquakes that hit the Peruvian territory in the past. In Peru, information of historical events can be found since 1500. For these events the date of occurrence is known, and can be used to assess the rate of recurrence and the seismicity of a region. This information was gathered by Silgado (1978) and Dorbath et al (1990). According to these authors, the largest earthquakes are the 1586 (first major earthquake with historical documents), 1687 and 1746 earthquakes. The 1746 event destroyed a large percentage of the city of Lima, and produce tsunamis with waves possibly reaching heights of 15-20 meters. In the southern region, the most notable earthquakes occurred in 1604, 1784 and 1868, the latter being the best documented and described in detail by Montessus de Ballores (1911) and Vargas (1922). The 1868 earthquake would have generated tsunami with waves 14 meters high affecting Tacna (Peru), Arica and Iquique (Chile) departments.

### 3.2.- Instrumental seismicity

Data from 1960 was available, at global and regional level of an acceptable number of seismic stations whose information helped reduce errors in the calculation of the parameters that characterize an earthquake. In the case of Peru, the basis of seismic data in the 60s was the catalog of the Global Seismic Network (USGS), while in the 80s, with increasing operating local seismic stations, quality of information improved considerably. For this study, it is considered the following seismic data:

- Before 1900 historical data of destructive earthquakes (Silgado, 1980; Dorbath et al, 1990) are available.
- Between 1900 and 1960 data is available from the USGS Network, which allowed roughly estimation of seismic parameters (USGS, Engdahl y Villaseñor, 2002).
- Between 1960 and 2012: data is available from local stations and thus more accurate instruments, improving seismic database (Engdahl y Villaseñor, 2002; IGP).

## 4.- Homogenizing Database

To evaluate the consistency of seismic database to be used in this study the software ZMAP V6.0 (Wiemer, 2001) was used, considering data for date, depth and magnitude of each seismic event. For example, Fig 2 shows the distribution of the cumulative number of events for historical and instrumental periods shown. It is clear that from the year 1960, the detection capability has increased, which effectively improves calculation of the hypocentral parameters of earthquakes in Peru.

In Fig 3a histogram of depth levels are shown. The number of shallow earthquakes is clearly greater than other events whereas, in Fig 3b, shows that the highest number of events has magnitudes between 4.25 and 4.75 Mw.

As data contained in the seismic catalog is assume to have a Poisson distribution, it was necessary to purge the aftershocks associated with large events and it was made using relations proposed by Utsu (1970) y Maeda (1996).

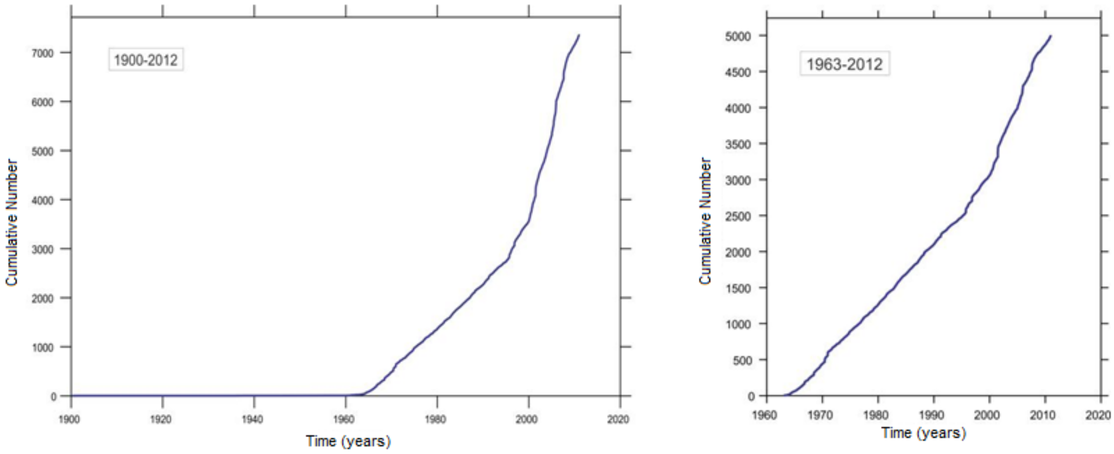


Fig. 2 – Time distribution of seismic events considered in the seismic catalog.
a) Period 1900 to 2011 y b) Period 1963 to 2011

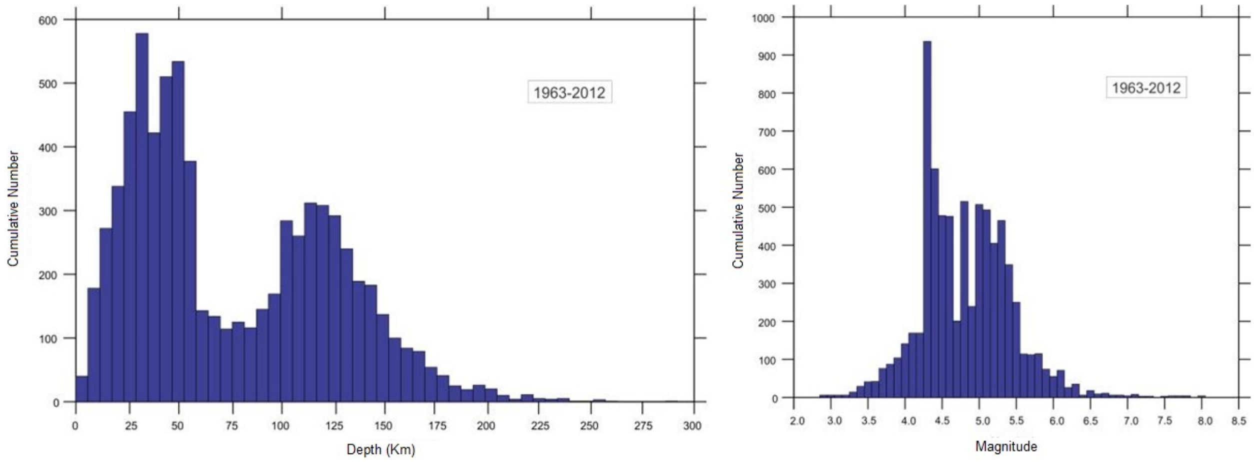


Fig. 3 – a) Earthquake frequency histogram of the depth of recorded earthquakes
b) Earthquake frequency histogram based on the magnitude

## 5.- Sources And Parameters Seismological Seismogenic

Seismogenic sources can be defined as either a line, a polygon or a volume with geological, geophysical and seismic similarities, so it can be said that their seismic potential is homogeneous throughout the source.

The definition of these sources was carried out according to the spatial distribution of seismicity associated with the process of subduction (interface earthquakes), taking into account the geographical location of large earthquakes and changes in the pattern of spatial distribution seismicity according to Tavera and Buforn (2001), Tavera and Bernal (2002), Quispe and Tavera (2003), Condori and Tavera (2010), Guard and Tavera (2013). For continental seismogenic sources associated with shallow crustal deformations, it has been considered the spatial distribution of the various geological faults systems proposed by Macharé et al (2003) and Tavera and Bernal (2002). In this case, although for some areas seismicity is scattered, it has been possible to regroup in seismogenic sources properly.

In this study 33 new seismic sources were defined based on the spatial distribution of seismicity associated with subduction (interface), major fault systems (cortical) and the geometry of the Nazca plate beneath the continent (intraplate) (see Fig.4). Unlike previous studies, the intraplate seismicity affecting the city of Pucallpa, which had given rise to major earthquakes with magnitudes of 7.2Mw with side effects (landslides and soil liquefaction), has been considered independently as a seismic source.

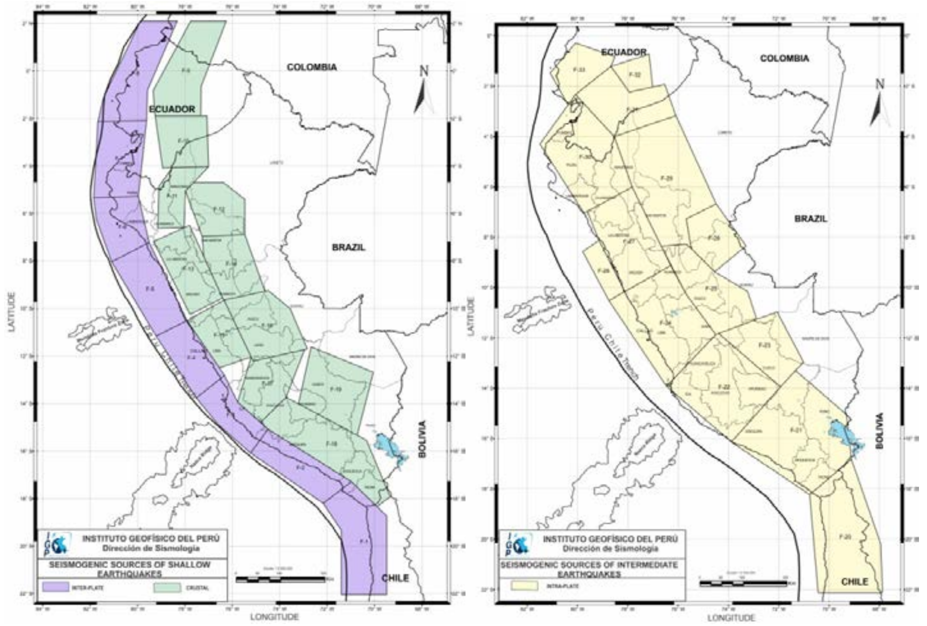


Fig. 4 – Shallow and intermediate focus seismicity and distribution and geometry of subduction and crustal sources

The seismic recurrence in a source, Log N = a - bM, quantifies the number of events greater than or equal to a given magnitude, defined by the slope (b) of the curve (Gutenberg and Richter, 1956). The relationship allows knowing the annual average rate of seismic activity ($\lambda_o$) and the minimum and maximum magnitude ($M_o$, $M_{max}$). It is expressed as follows:

$$N = \Gamma_o e^{-\beta M} \qquad \text{Eq. (5)}$$

where, $\Gamma_o = 10^a$, is the number of earthquakes per unit time $M>M_0$

$$\beta = b.Ln10 \qquad \text{Eq. (6)}$$

For seismic recurrence curves, the database for historical earthquakes is considered using statistical average instrumental seismicity (Reiter, 1990; Kramer, 1996). This procedure allows incorporating historical information to a limited catalog and not extending the period of completion of the catalog.

The largest magnitude in each source is a parameter that is difficult to establish based on recorded data. In this model, it is consider that the maximum magnitude is uncertain, and can vary from a minimum which is the highest magnitude recorded, and a maximum value proposed based on publications on seismic coupling and probability of occurrence of large earthquakes on the western edge of Peru (Chlieh et al 2011 areas; Pulido et al 2012; Condori and Tavera , 2012; Flores and Tavera, 2012). Regarding the magnitude of historical earthquakes, the contribution of Dorbath et al (1990) was considered. To set the minimum and maximum levels of depth of each source, it was necessary to evaluate the distribution of seismicity in depth according to the criteria established by Cahill and Isacks (1990), Tavera and Bufron (2001), Condori and Tavera (2012); Guard and Tavera, (2012).

## 6.- Probabilistic Seismic Hazard

The Seismic Hazard was evaluated with the proposed method proposed by Esteva (1968), Cornell (1968) and Cornell & Van Marcke (1969). According to this, the seismic hazard at a specific point is the probability that a given intensity level be reached or surpassed,

On the other hand, the intensity (I) of an earthquake at a particular location is considered dependent on the size of the earthquake (magnitude) and the distance to the point of interest. The size of the earthquake (s) and location (r) are considered as continuous random variables and defined by its probability density function, fs (s) and fr (r); then the seismic hazard defined as the probability that the intensity I is equal to or greater than a given intensity will be P(I≥i) and is defined by (Esteva, 1968):

$$P(I \geq i) = \iint P\left[\!\left[\frac{I}{s,r}\right]\!\right] fs(s).fr(r)dsdr \qquad \text{Eq. (7)}$$

In Peru, various GMPEs have been used and mostly from other seismotectonic environments. Some proposed GMPE have been constructed using data from accelerometer stations operating in the city of Lima and recorded the major earthquakes that occurred between 1940 and 1974.

An evaluation of these GMPEs was conducted by Alva (2005). The author highlights the significant differences, especially when it comes to return periods greater than 100 years. According to these results, the GMPEs of Young et al (1997) and Sadigh et al (1997) averages for all GMPEs evaluated; therefore, in this study we proceed to use both GMPE.

## 7.- CRISIS-2007

The seismic hazard in Peru is calculated using CRISIS-2007 (Ordaz et al, 2007) considering the sum of the effects of all the seismic sources and the distance between each source and points of interest to be evaluated.

The graphic environment of CRISIS-2007, with dialog boxes, facilitates data processing and calculation of seismic hazard. Seismic hazard maps, as that shown in Fig. 5, enable us to know the acceleration (intensity) for different return periods and structural periods and Uniform Hazard spectra at any location within the analyzed region.

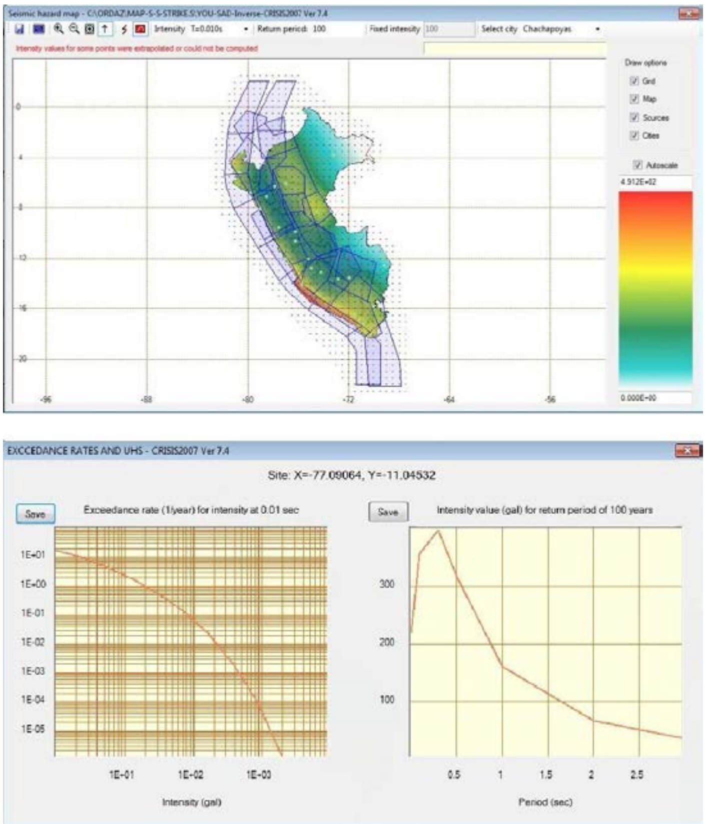


Fig. 5 – Screenshot of CRISIS-2007 showing the map of seismic hazard for Peru; in addition to the curve of the exceedance rate and uniform hazard spectrum for a given point

Seismic hazard maps are obtained from the evaluation of the annual frequency of exceedance of different intensity levels (Sa), combined with the Poisson distribution to estimate the annual exceedance probability (Kramer, 1996; Gamarra, 2009).

## 8.- Isoacceleration In Peru

The map of seismic hazard for Peru, in terms of the horizontal peak ground acceleration or PGA, obtained using the parameters defined in previous chapters with a mesh of nodes spaced every 0.1° and the program CRISIS-2007 (Ordaz et al, 2007) is shown in Fig. 6 for a return period of 475 years. In general, acceleration curves follow the same pattern observed in studies developed by Castillo and Alva (1993) and Gamarra and Aguilar (2009), which are:

- Acceleration Curves are distributed parallel to the coastline, following the direction in which the subduction of the Nazca plate beneath the South American occurs.
- The acceleration values decrease gradually as they move towards the inland.
- The acceleration values, close to the waterfront, are lower in the northern region and greater in the southern region, which agrees with the areas of greatest occurrence of earthquakes.
- In the north-eastern region, acceleration curves are concentrated in the region of Alto Mayo (department of San Martin) and is due to the presence of the fault system Rioja-Moyobamba and that gave rise to earthquakes of 1990 ( 6.2Mw) and 1991 (6.5Mw).
- The acceleration curves are concentrated in the northern end of the department of Ucayali and correspond to nest intermediate seismicity occurs below the city of Pucallpa to levels of 100-150 km deep.
- The peak ground acceleration values should be considered as an average value on solid ground (PGA), without considering the effects of site and soil-structure interaction.
- For large infrastructure projects, it is recommended to carry out specific studies for seismic hazard in order to be representative of the scale and the high costs of the works.

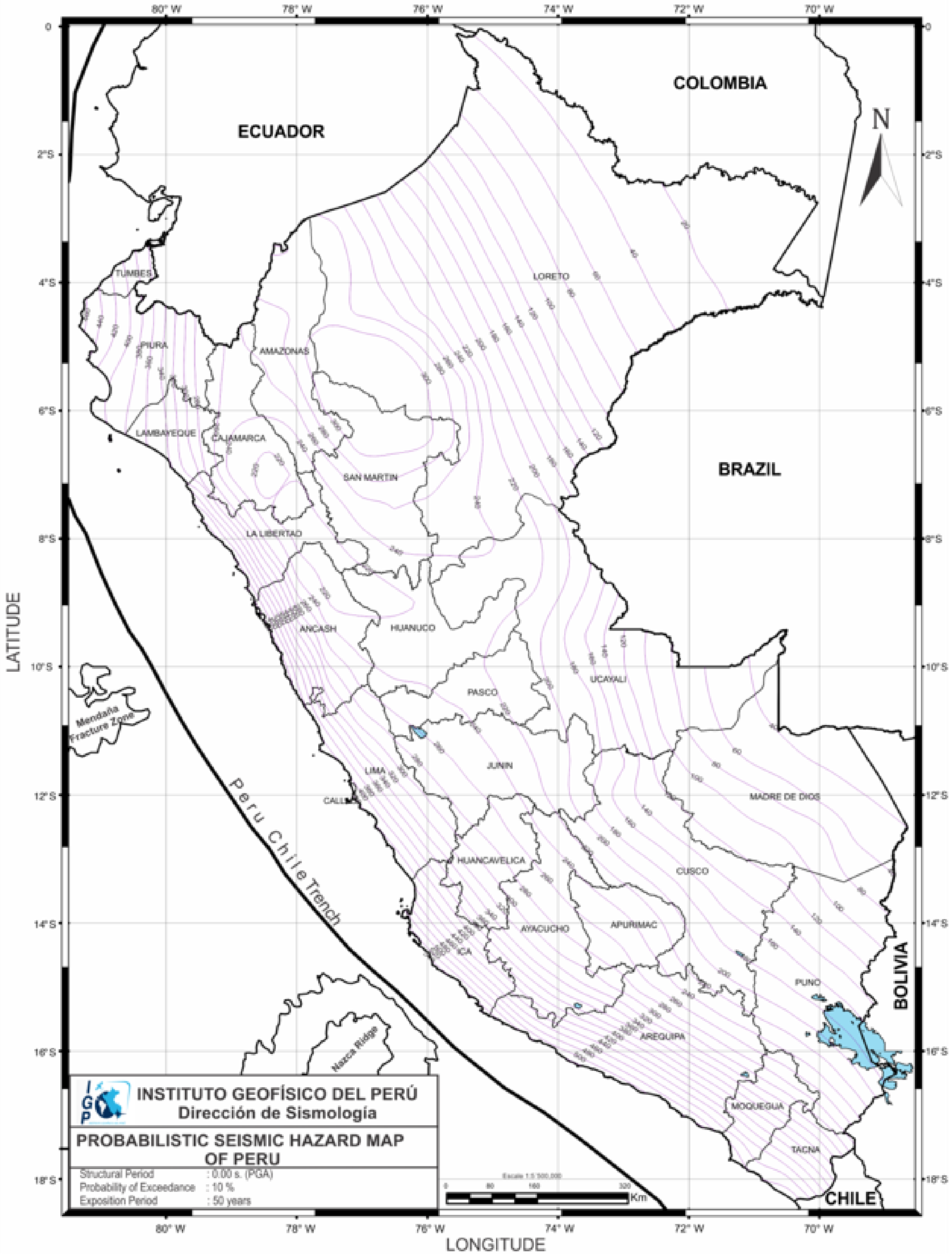


Fig. 6 – Seismic hazard map for Peru considering a return period of 50 years with 10% exceedance. The acceleration values are expressed in units of gals.

## 9. Uniform Hazard Spectra

A Uniform Hazard Spectrum UHS is a spectrum that has the same probability of being exceeded in all structural period. This takes into account the possible combinations between the magnitude and distance of the earthquake to the point of interest; therefore, it can be used in a spectral analysis of structural response.

For Peru, the Uniform Hazard Spectra were developed for a range of different spectral periods (PGA, 0.1, 0.2, 0.3, 0.4, 1.0, 2.0, 3.0, etc.), for the same probability of exceedance. With this model, UHS where determined for several return period for any location within Peru.

## 10. Conclusions

- The spatial analysis of seismicity and seismotectonic evaluation of Peru, have allowed to identify and define the geometry of 33 seismogenic sources associated with the interface seismicity, intraplate seismicity and crustal deformation. For these sources, the seismological parameters have been determined using statistical regressions.
- According to the analysis performed for Alva (2005), in this study the GMPEs proposed by Young et al (1997) and Sadiq et al (1997) were used.
- The seismic hazard maps obtained in this study can be considered as a basic input for the development of engineering projects and major infrastructure in Peru.
- Uniform hazard spectra must be properly integrated in the processes of structural design. For this purpose, the results of this study can be considered an important contribution.
- Microzonation studies in major cities in the country are necessary to achieve greater understanding of this issue in widely populated areas.
- In Peru, the largest population and industries are located in areas of high seismic hazard, then it is important to make use of studies of seismic hazard assessments for disaster risk reduction purposes thereof. It is understood that the danger may be constant over time, but the exposure and vulnerability of the population are continuously increasing.
- Efforts should be made to achieve integration of professionals of various fields to increase the information available necessary to improve risk management studies.

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