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Probabilistic Seismic Hazard Assessment in the Peruvian Territory

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Abstract

This paper presents new probabilistic seismic hazard estimates for Peru. Available geological and seismological data have been used to evaluate and characterize twenty nine seismic sources. An earthquake catalog has been compiled covering the time span between 1555 to 2016 AD and for the area bounded by 66°W - 84°W and 4°N - 23°S. Ground motion prediction equations appropriate for subduction and crustal zones have been selected. Probabilistic seismic hazard maps have been derived for the Peruvian territory and depict peak horizontal ground acceleration and spectral response at 0.2, and 1.0 sec periods with 10 % and 2 % probabilities of exceedance in 50 years. The final result of this assessment consists of a Peruvian seismic hazard web application. This free application allows users to obtain seismic hazard curves: Annual Frequency of Exceedance vs Spectral Acceleration, Uniform Hazard Response Spectra, and Seismic Design Spectra for any location in Peru, in accordance with the Peruvian Seismic Code E-030, 2016[1]. and the IBC, 2012[2]. provisions. Calculations consider different damping coefficients and are obtained for a 0.1° longitude-latitude grid in the Peruvian territory. The hazard curves supplied by this application may be retrieved in CSV, XLS, TXT, PDF, and JPGE formats and can be used as a preliminary site-specific seismic hazard analysis.

Keywords: seismic hazard, seismic design code, probabilistic seismic hazard assessment, web application.

1. Introduction

Peru is located on the western edge of the South American crustal plate which is one of the most seismically active region in the world. The subduction process of the Nazca plate beneath the South American plate is the major source of large and destructive earthquakes in the Peruvian territory, therefore, a proper understanding of the level of seismic hazard and its corresponding dissemination throughout the country is necessary.

Seismic design in Peru is based on the Peruvian Seismic Desing Code (PSC) E-030, 2016 which considers a four-fold macrozoning with different Zone Factors (Z) assigned for a 10 % exceedance probability in 50 years (475-year return period). So, in this research, seismic hazard maps have been developed in order to show a more detailed distribution of the seismic hazard, and a web application have been programmed in order to disseminate, in a dynamic way, seismic hazard curves and seismic design spectra obtained for a 0.1°-Longitude-Latitude grid in accordance with the PSC, 2016 and the IBC, 2012 provisions.

2. Earthquake Catalog and Seismic Source Zone Characterization

2.1 Earthquake catalog

An earthquake catalog has been compiled for the period from 1555 to 2015 and for the area bounded by 66°W–84°W and 4°N–23°S, this information have been collected from different sources such as Geophysical Institute of Peru (GIP), International Seismic Center (ISC), National Earthquake Information Center (NEIC), United States Geological Survey (USGS), National Oceanic and Atmospheric Administration NOAA and Global CTM. The size parameter has been homogenized to moment magnitude (Mw) using the relations of Scordilis *et al*. (2006)[3] (M_S, m_b to Mw) and the considerations of Boore, D.; and Joyner W. (1982)[4] (M_L to Mw).

The seismic hazard assessment methodology considers the assumption that the probability of the occurrence of an earthquake in a given period of time follows a Poisson distribution. Thus the earthquake catalog must be free of dependent events such as foreshocks and aftershocks. The catalog was declustered using the algorithm of Reasenberg (1985)[5] and Maeda (1996)[6], then, it was manually removed duplicate events. After the homogenization, depuration and revision, the full project catalog contains 12 924 earthquake events of Mw ≥ 4.0 (see Fig. 1).

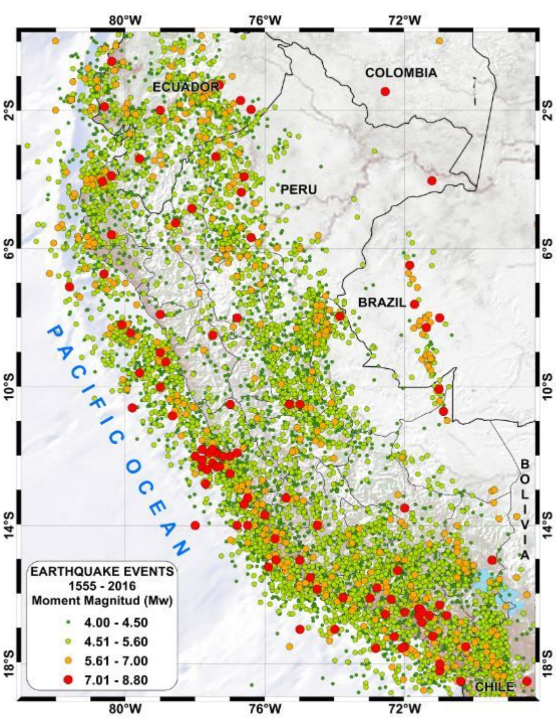


Fig. 1 – Earthquake catalog

2.2 Seismic Source Characterization

Seismic source characterization has been defined based on the analysis of earthquake locations and its focal mechanisms, the current understanding of the regional geology and tectonics. This study considers three groups of zones: crustal, subduction interface and subduction intraslab. Identification of crustal sources was based on regional quaternary faults identification whose results were published in *Descriptive Summary of Neotectonic Map* (Macharé *et al*. (2008))[7] (see Fig. 2).

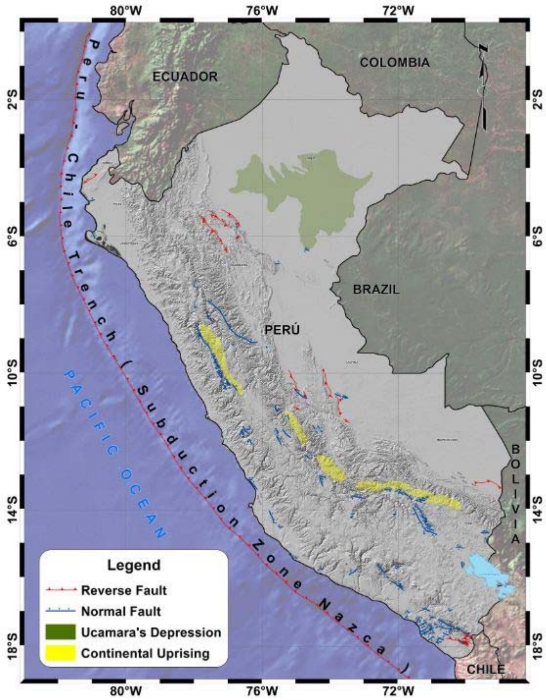


Fig. 2 – Neotectonic Map (Macharé *et al*. (2008))

This study considered twenty-nine seismic areal sources. Areal source zones are regions where earthquakes are assumed to occur randomly. For this study, subduction interface sources are listed from 1 to 6, subduction intraslab sources are listed from 7 to 20, whose geometry is consistent with Cahill and Isacks's (1992)[8] subduction model. The other nine seismic sources where considered to represent the crustal seismicity which are listed from 21 to 29 (see Fig. 3).

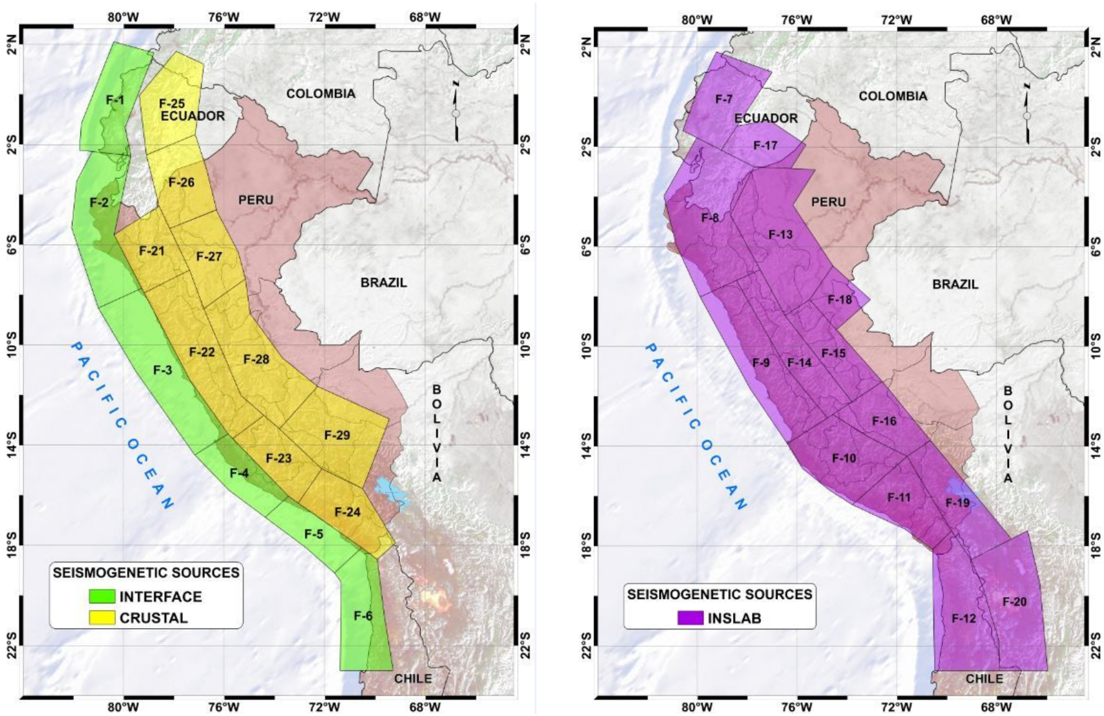


Fig. 3 – Seismic subduction and crustal source delineations

3. Seismic Parameters and Earthquake Recurrence

The main target of an earthquake recurrence analysis is estimate the frequency of earthquake occurrence in a seismic source. For this study, the Gutenberg and Richter non-truncated model was used to characterize the earthquake distribution and recurrence within each seismic source zone.

The seismic source parameter Maximum Magnitude "M_{max}" is defined as the biggest event that can be occurred in a seismic source (McGuire, 1976[9]). Furthermore, the Minimum Magnitude "M_{min}" was determined as the point of maximum curvature of a frequency distribution analysis of magnitudes (Wiemer and Katsumata, 1999[10]). Maximum magnitude assigned to subduction zone is 8.4. Meanwhile, for shallow crustal the maximum magnitude is 7.4.

The *b*-value and the seismic event rate "μ" for different periods of observation and different magnitudes were determined using the maximum likelihood method proposed by Weichert (1980)[11]. The statistical completeness of the catalog has been assessed using Stepp (1972)[12] methodology; this assessment shows that the reported earthquake magnitudes are incomplete for the same periods. The completeness of earthquake catalog is shown in Table 1.

Table 1 – Magnitude completeness of historical and instrumental earthquakes.

Magnitude interval	Complete since
[4.0 – 4.9]	1964
[5.0 – 5.9]	1960
[6.0 – 6.9]	1954
[7.0 – 7.9]	1906
[8.0 – +]	1555

4. Ground Motion Prediction Equations (GMPEs)

Ground Motion Prediction Equations are used to estimate probabilistic and deterministic seismic hazard for a specific site. The GMPEs have been selected according to the tectonic regime associated with the earthquakes in each seismic source. For this study, the GMPEs developed by Youngs *et al.* (1997)[13], McVerry *et al.* (2006)[14], Zhao *et al.* (2006)[15] and Abrahamson *et al.* (2015)[16] were used to estimate the horizontal ground motion and spectral accelerations from subduction interface and slab zones. Logic tree weights assigned to these models are 0.30, 0.35, 0.15, and 0.20, respectively in the PSHA.

For crustal zones, Sadigh *et al.* (1997)[17] and Campbell and Bozorgnia (2008)[18] were used. Equal logic tree weights of 0.50 have been assigned for each model.

GPMEs considered a Site Class B (rock), as defined in the International Building Code [IBC] (2012) and the American Society of Civil Engineers [ASCE 7] (2010)[19].

5. Probabilistic Seismic Hazard Assessment

The seismic hazard assessment was carried out following the probabilistic methodology of Cornell (1968) [20] and through the CRISIS 2015 v.2.2 computational program (Ordaz *et al.*, 2015[21]) in points of a grid covering the Peruvian territory, equally spaced at 0.1° in longitude and latitude.

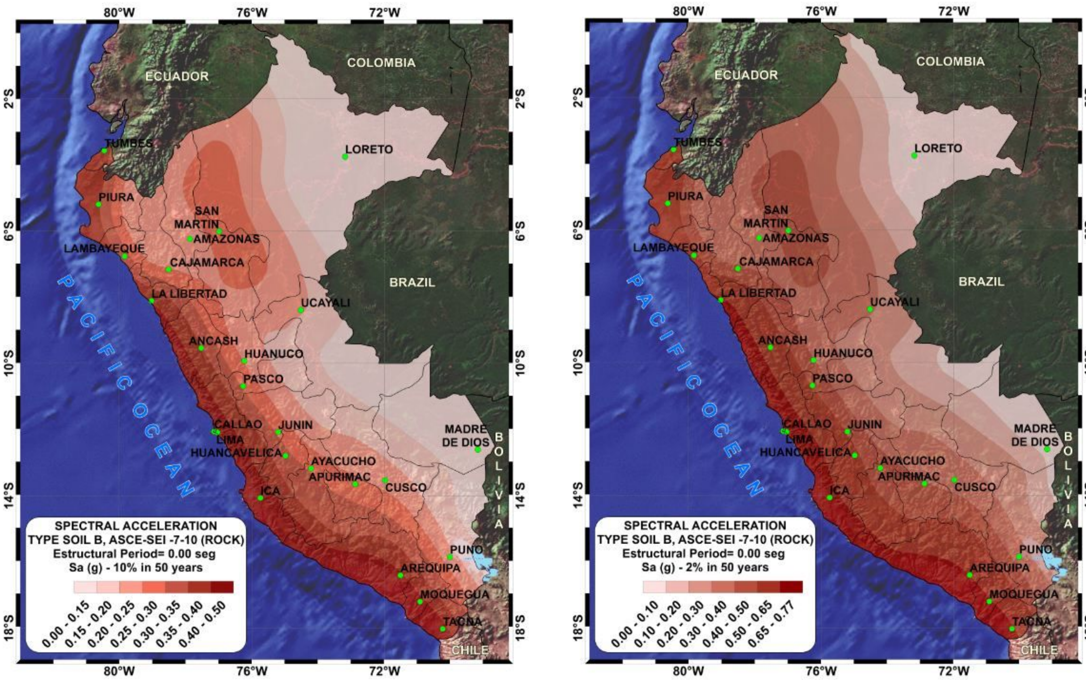
The results of the PSHA are commonly presented in terms of ground motion as a function of annual exceedance probability. The spectral acceleration (5 % damping) PGA(0.0 s), Sa(0.2 s) and Sa(1.0 s) for some of the main cities of Peru are shown in Table 2.

Table 2 – Spectral Acceleration Parameters – 475 and 2475 Years Return Period – Site Class B

CITY	10 % Probability of exceedance in 50 years			2 % probability of exceedance in 50 years		
	Spectral Acceleration - Sa (g)			Spectral Acceleration - Sa (g)		
	PGA (T=0.0 s)	Sa (T=0.2 s)	Sa (T=1.0 s)	PGA (T=0.0 s)	Sa (T=0.2 s)	Sa (T=1.0 s)
LIMA	0.43	1.17	0.3	0.71	1.99	0.5
AREQUIPA	0.41	1.11	0.29	0.65	1.84	0.46
JUNIN	0.29	0.81	0.19	0.49	1.41	0.32
PUNO	0.22	0.58	0.15	0.35	0.97	0.24
CAJAMARCA	0.26	0.69	0.19	0.43	1.19	0.31
TUMBES	0.37	0.92	0.29	0.6	1.54	0.49
TACNA	0.42	1.13	0.32	0.67	1.85	0.52
CUSCO	0.23	0.62	0.15	0.35	0.98	0.24

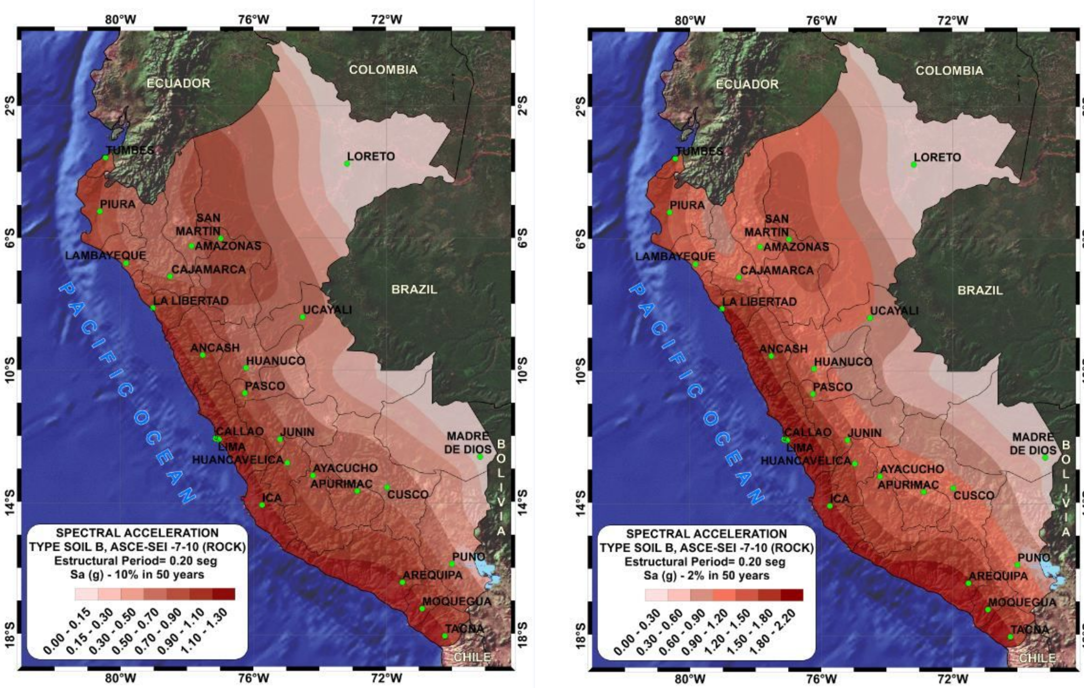
6. Development of Seismic Hazard Maps

Seismic hazard maps have been produced by considering a 2 % probability of exceedance in 50 years. Most of the seismic codes use these hazard values commonly termed as maximum considered earthquake (MCE) which is then reduced by correlation factors to estimate the design basis earthquake (DBE). Also seismic hazard maps with a 10 % probability of exceedance in 50 years (corresponding to a return period of 475 years) where represented for PGA, Sa(0.2 s) and Sa(1.0 s) (see Figures 4, 5 and 6).



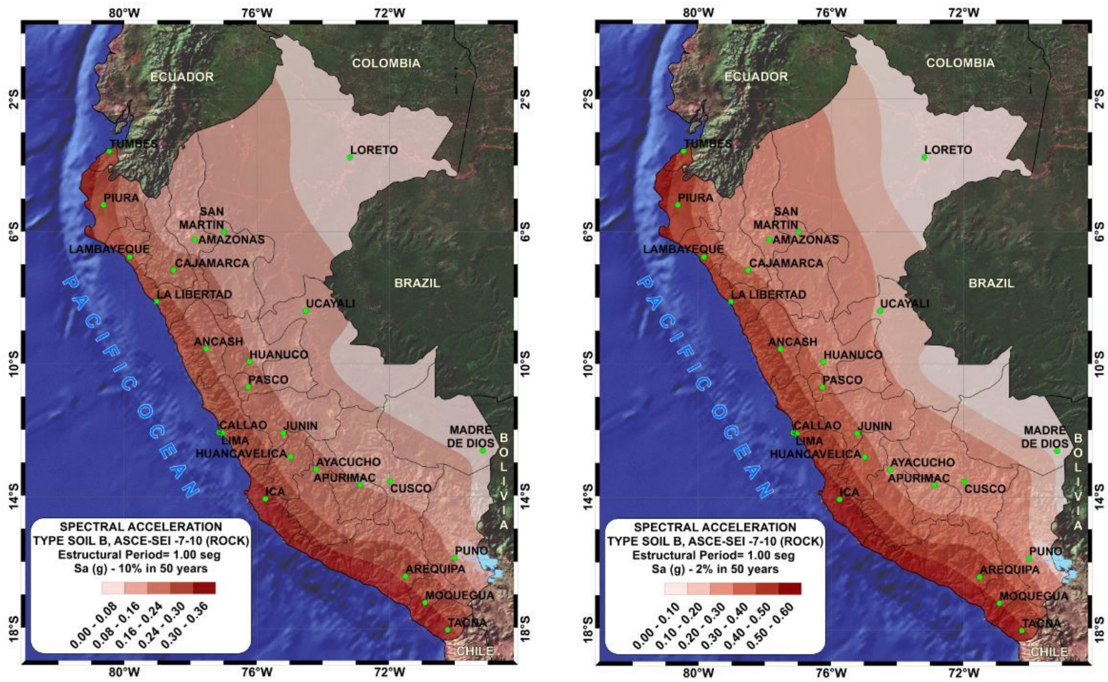
(a) (b)

Fig. 4 – Spectral Acceleration Maps for 0.0 s (PGA). (a) 475 year return period; (b) 2475 year return period



(a) (b)

Fig. 5 – Spectral Acceleration Maps for 0.2 s. (a) 475 year return period; (b) 2475 year return period

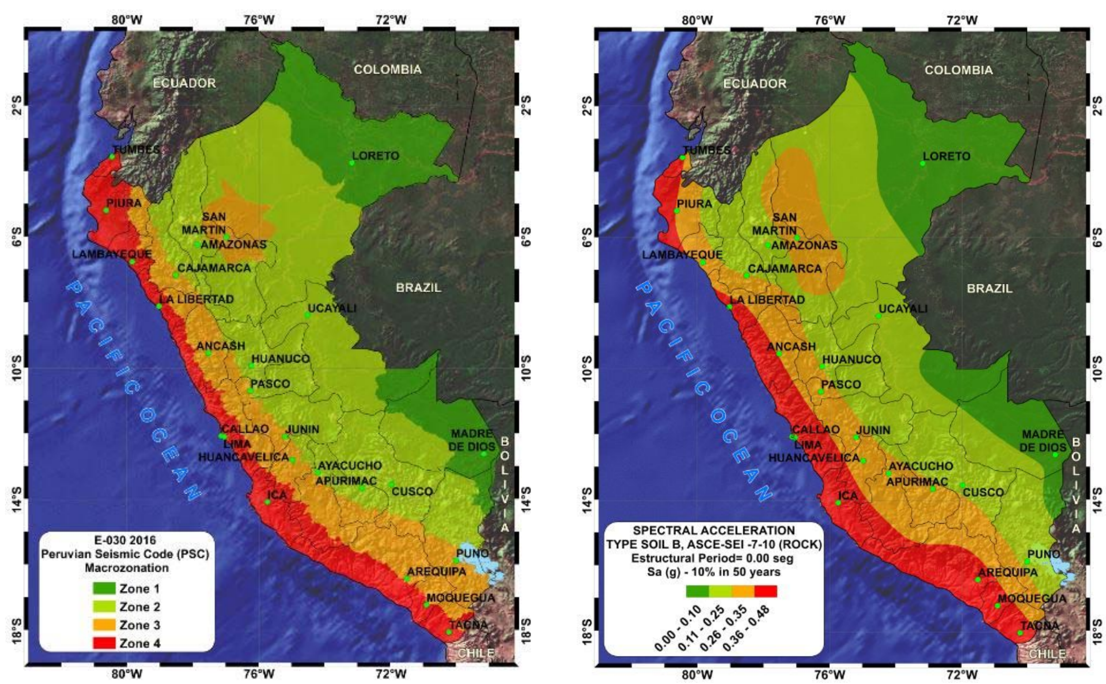


(a) (b)

Fig. 6 – Spectral Acceleration Maps for 1.0 s. (a) 475 year return period; (b) 2475 year return period

6.1 Peruvian Seismic Macrozoning Map

The E-030 2016 Peruvian Seismic Code (PSC) defines a four-fold macrozoning with seismic factors (Z) expressed as the PGA, considering a 10 % exceedance in 50 years. By comparison, a seismic macrozoning map is presented with PGA's boundaries defined by a fraction of gravity acceleration 0.15 g, 0.25 g, 0.35 g and 0.45 g. The lowest value of the PGA are in the east (Zone 1), and the highest in the west (Zone 4).



(a) (b)

Fig. 7 – Peruvian Seismic Macrozonation Map. (a) PSC E-030, 2016; (b) This study

6. Web Application

As part of this project, the web application “CPSP” has been programmed witch can be accessed from anywhere in the world on the website www.sencico.gob.pe. This free application allows users to obtain valuable Peruvian seismic hazard information like:

- Annual Frequency of Exceedance (AFE) vs Spectral Acceleration (Sa),
- Uniform Hazard Response Spectra (UHRS), and
- Seismic Design Spectra (SDS) in accordance with the PSC, 2016 and the IBC, 2012 provisions.

This web application provides hazard curves for a specific site defined by an equally spaced 0.1° longitude-latitude grid in the Peruvian territory (See Fig. 8). AFE vs Sa curves can be drawn for different damping coefficients (ξ) from 2 % to 10 % and for different structural periods from 0.0 s to 3.0 s. UHRS can also be evaluated for the same range of damping coefficients and for any return period from 50 to 10 000 year return period (See Fig. 9). Finally, SDS can be obtained in accordance with the IBC, 2012 provisions or the PSC E-030, 2016 which the latter considers a four-fold macrozoning with four seismic factors (Z), or the option of obtaining SDS based on a “site-specific Z value” for any point of the grid considering a 10 % exceedance in 50 years (475 year return period) following the methodology of the PSC E-030, 2016. SDS is presented for different site class. (See Fig. 10).

The hazard curves supplied by this application may be retrieved in CSV, XLS, TXT, SVG, PDF, PGN, and JPGE formats and can be used as a preliminary site-specific seismic hazard analysis.

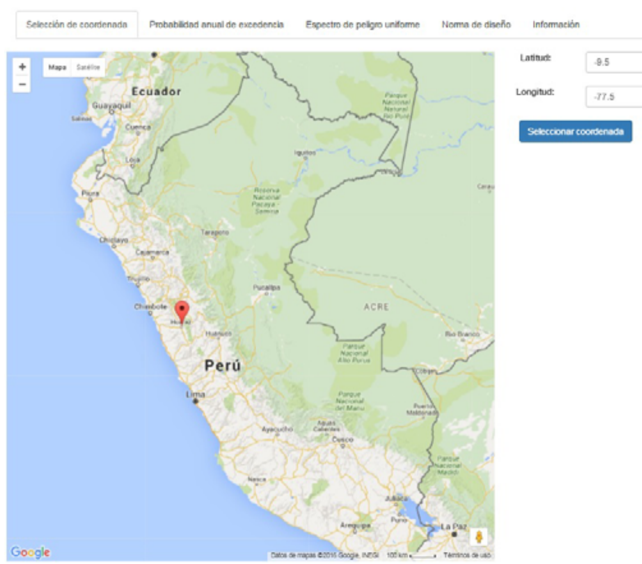
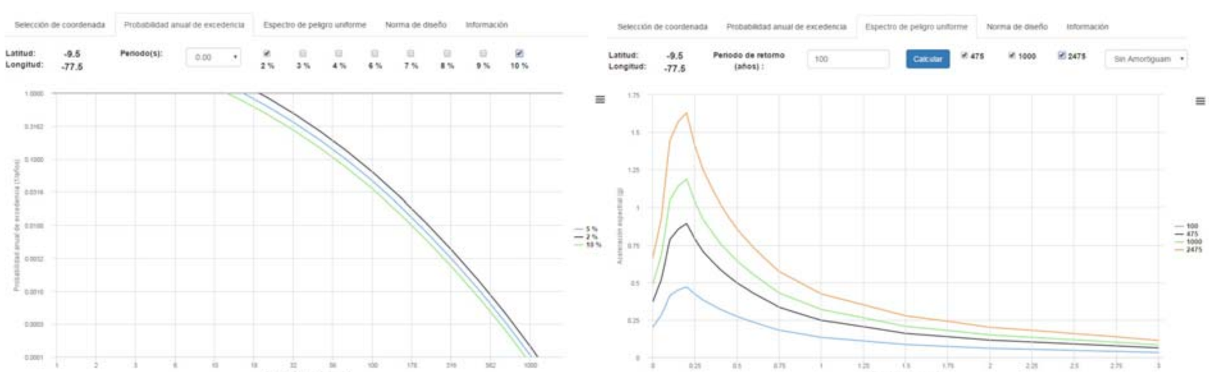


Fig. 8 – Set Location. Equally spaced 0.1° longitude-latitude grid in the Peruvian territory



(a) (b)

Fig. 9 – Web application output. (a) Annual Frequency of Exceedance vs Spectral Acceleration. (b) Uniform Hazard Response Spectra

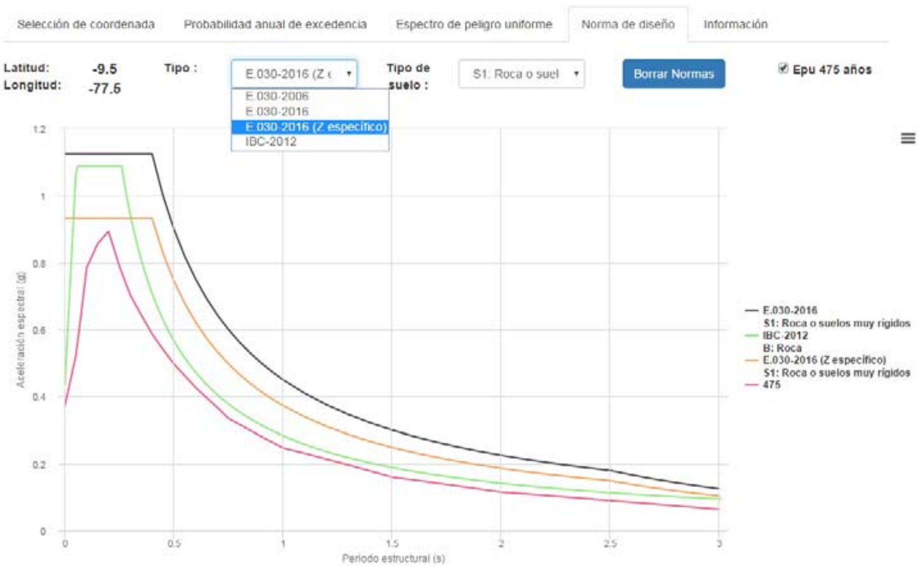


Fig. 10 – Web Application Output. Site-Specific Seismic Design Spectra in accordance with the PSC, 2016 and the IBC, 2012 provisions, and UHRS for a return period of 475 years

5. Conclusions

Seismic hazard maps show that the probabilistic hazard is expectedly high in coastal Peru. Isolines are quite parallel to the coast and spectral acceleration decreases towards the continent except for the North Central Peruvian region which has the influence of important quaternary faults and high Mw magnitude registered. The PSHA show that the highest spectral acceleration values are expected for Piura, Lima, Arequipa and Tacna.

The four-fold macrozoning defined by the PSC E-030, 2016 is similar to that obtained in this study, however, the free "CPSP" web application developed in this study allows users to obtain seismic hazard information for a 0.1° x 0.1° grid and several damping coefficients. The probabilistic seismic hazard analysis developed in this study can be found on the website www.sencico.gob.pe and can be used as a preliminary site-specific seismic hazard analysis. This computer application will become in a very useful tool for the professional community to estimate the seismic hazard and to obtain the seismic design parameters for their projects located anywhere in Peru.

6. Copyrights

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