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Seismic Microzonation of Pisco City and San Clemente, Tupac Amaru, San Andres and Paracas Districts

A. Renmin Pretell Ductram¹, Zenon Aguilar Bardales²

ABSTRACT

This article focuses on the seismic microzonation of Pisco City and surrounding areas in Ica, Peru. Geological, geotechnical and geophysical data have been collected from comprehensive geotechnical and geophysical field investigations and laboratory tests. This information was evaluated to produce soil type zones along with isoperiod zones maps. In addition, seismic hazard assessment and seismic response analyses for the area were conducted for structural design and comparison with Peruvian Code purposes. Four zones with different level of hazard were proposed to develop a seismic microzonation map for Pisco City.

Introduction

Peru is located on the Pacific Ring of Fire along the South America and Nazca plate. The active seismicity of this zone has caused major earthquakes in Peru. Recently, on August the 15th 2007, Pisco was struck by one of the strongest earthquakes ever registered in Peru, having M_w 7.9 magnitude according to the Peruvian Geophysical Institute (M_w 8.0 reported by the National Earthquake Information Center NEIC) and causing more than 500 human fatalities (USGS). Thus, the purpose of this research is to develop a seismic microzonation map for Pisco City and its surrounding areas based on field and lab geotechnical data as well as seismic hazard and seismic response analysis to prevent future disasters by informing the development of this region in Pisco. Methodology consists of three main steps: (1) data collection, (2) information processing and interpretation, and (3) disciplines integration to develop a seismic microzonation map. Four zones were identified, associated to with different hazard levels for the study area; characteristics are presented and discussed. Furthermore, seismic response analyses results are compared with NTP E.030 Peruvian Code design spectrum.

Location of the Study Area

This research was conducted in Pisco city and surrounding areas, located 200 km to the south of Lima, in Ica region. Surrounding areas include El Carmen, San Clemente, Tupac Amaru Inca, San Andres and Paracas. The covered area is about 334 km², which represent nearly one tenth of Pisco province. Figure 1 shows the location of study area.

Geology of the Study Area

Three major geomorphological units can be found in the study area: Coastal range, coastal

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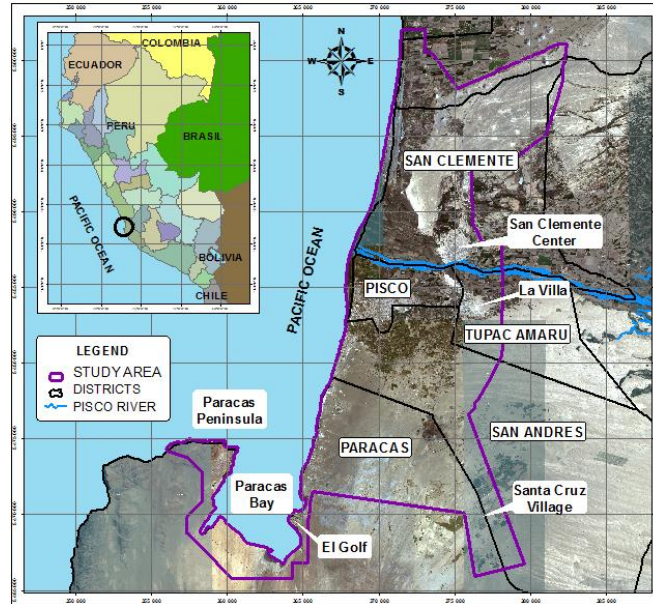


Figure 1. Location of the study area.

penneplain and valleys. They lie orthogonally to Andean foothills, present little depth and wide extension.

Lithologically, alluvial and eluvial deposits are the most extensive deposits in the area. Fluvial, marine and aeolian deposits are found in minor extent. Additionally, outcrops of diatomite rock and an erratic configuration of rocks in the Paracas peninsula are found (Fernandez, 1993).

Geotechnical Investigation

A total of 131 investigation points were strategically located to cover the study area. In them, trial pits and trenches were performed together with DPL, SPT and sand cone density tests. Soil characteristics including particle size distribution, plasticity index (PI), soil classification (USCS) and layer depth were collected and analyzed to produce the map of Soil Type Zones (see Figure 2). For regional soil profile mapping, 13 different soil zones were identified including: rock outcrops, dense gravels, medium to dense deep sands, dense silty sands, silty sands thinner than 1.5 m, silty sands between 1.5 and 4.0 m thick, silty sands thicker than 4.0 m, alluvial sand and gravels, marine deposits, potentially liquefiable sands, anthropogenic fills and wetlands. Outcrops of diatomite were also found.

Geophysical Assessment

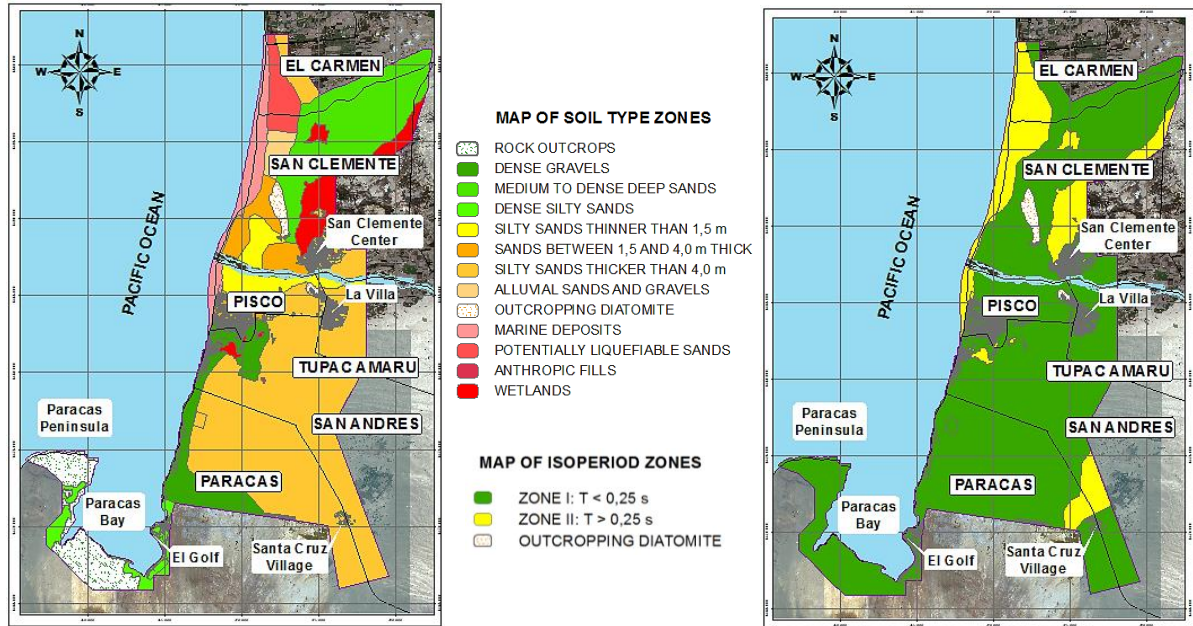
Geophysical data mainly consisting of MASW tests and microtremor measurements were collected. Soil fundamental period values were obtained from Nakamura spectral ratio of orthogonal measured signals, relation shown in Equation 1 (Nakamura, 1989),

$$\frac{H}{V} = \sqrt{\frac{(v_{E-W})^2 + (v_{N-S})^2}{(v_Z)^2}} \quad (1)$$

where H/V is the Nakamura spectral ratio, V_{E-W} , V_{N-S} and V_Z the two horizontal and vertical components of measured microtremors signal respectively.

Amplification factors were also estimated from spectral ratio, however they should be considered only as a reference since microtremor measurements are more influenced by noise source than soil characteristics (Lachet and Bard, 1994).

Fundamental period of soils varies between 0.08 and 0.15 s, but several values between 0.05 and 0.35s were found. This information was classified in two groups as shown in Figure 3.



Left: Figure 2. Map of soil type zones.
 Right: Figure 3. Map of isoperiod zones.

Zone I, which encompasses more than 75% of the total study area, includes soil profiles whose fundamental period is shorter than 0.25 s. Here, amplification factors obtained by means of Nakamura spectral ratio vary between 3.0 and 5.0 for a range period from 0.08 to 0.15. Zone II presents areas with fundamental periods larger than 0.25 s and amplification factors of 2.5 and 5.5 between periods of 0.25 and 0.30 s. Diatomite rock has not been classified as Zone I or II because of its variable behavior dependent on moisture content; however microtremors measurements show fundamental periods shorter than 0.1 s in very low moisture content conditions, corresponding to higher stiffness of diatomite.

In addition, several profiles have been obtained from microtremor measurements. A maximum depth of 90 m was obtained by using F-K and SPAC processing techniques, which are increasingly used in Peru (Calderon, et al. 2011).

Seismic Hazard Analysis

Uniform Hazard Spectrum was obtained from National Service of Training for Industry and Construction (SENCICO) online tool, which provides engineers with USH for Peruvian territory by entering coordinates from the site of interest.

SENCICO's studies are based on a seismic catalog updated to October 2013, seismic sources proposed by Gamarra and Aguilar (2009) and subduction ground motion prediction equations developed by Youngs et al. (1997) and Zhao et al. (2006). Seismic hazard analysis was performed using CRISIS2007 (Ordaz et al., 1999) based on probabilistic methods (PSHA), for interface and intraslab subduction seismic sources associated with the most important events (i.e. Pisco 2007, Lima 1966, 1974 and 1993). The GSHAP algorithm (Dimat  et al., 1999) was used to remove dependent events and aftershocks from the seismic catalog, which contains events up to MMI IX such as the August 2007 event, occurred off Pisco coasts. Seismic hazard analysis was obtained for Site Class B (ASCE 7-05, 2005) and 475 years return period.

PSHA results presented in this article were compared with previous studies for the same location and similar site conditions. Table 1 shows this comparison for PGA as well as 0.2 second and 1.0 second spectral accelerations (S_a).

Table 1. PSHA results comparison.

Author	Ground Motion Prediction Equation	PGA (g)	S_a (T=0.2 s) (g)	S_a (T=1.0 s) (g)
Castillo and Alva (1993)	Casaverde and Vargas (1980)	0.44 – 0.46	-	-
Monroy et al., (2006)	Youngs et al., (1997)	0.42 – 0.44	0.94 – 0.98	0.38 – 0.40
SENCICO	Youngs et al., (1997) and Zhao et al., (2006)	0.44	1.05	0.40

Time histories of acceleration were generated by spectral matching process for the 475 years of return period uniform hazard spectrum previously described. Two earthquake records were selected for this purpose based on several criteria, most important: (1) earthquake source (Stewart et al., 2014), (2) magnitude, which has important influence on frequency content and duration but also in spectral shape (Bommer and Acevedo, 2004) and, (3) recording station site characteristics. Table 2 presents these criteria. SeismoMatch software (SeismoSoft, 2012) was used to perform spectral matching by using the wavelet algorithm proposed by Abrahamson (1992) and Hancock et al. (2006). Target, original and matched spectra are presented in Figure 4.

Table 2. Main criteria for earthquake records selection.

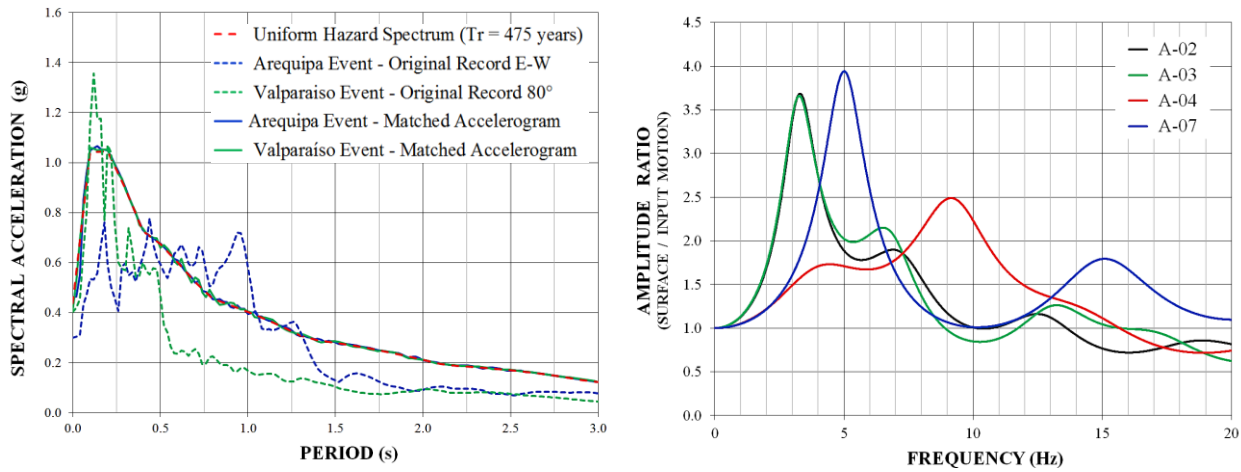
Event	Source	Magnitude	Station Name	Site Characteristics
Arequipa (2001)	Subduction interface	$M_w = 8.3$ (NEIC)	Cesar Vizcarra Vargas	Alluvial deposits, $V_{S30}=570$ m/s (Cortez-Flores, 2004)
Valparaiso (1985)	Subduction interface	$M_S = 7.8$ (RENADIC)	San Felipe	Dense gravel, alluvial deposits, $V_{S30}=500$ m/s (Arango et al., 2010)

Seismic Response Analysis

Equivalent-linear method was undertaken using DEEPSOIL (Hashash 2009) to perform four one-dimensional seismic response analyses considering shear wave velocity profiles obtained by geophysics tests. Analyses were performed considering the two cases compensate peaks and valleys presented in different spectra relative to target (Case 1: Arequipa 2001 event, Case 2: Valparaiso 1985 event). Input motion depth was defined based on shear wave velocity (V_S) in accordance to seismic hazard analysis for Site Class B ($V_S > 760$ m/s).

Darendeli's formulation (2001) for normalized shear modulus reduction and damping ratio curves has been considered for sandy materials while Rollins' (1998) for gravelly soils. Dynamic properties should be carefully chosen according to material characteristics since different proposals could cause great impact on results (Pretell et al., 2012).

Transfer functions, defined as the output to input Fourier spectra ratio, were found to be pretty similar for the two cases, then Figure 5 shows transfer function corresponding to Case 1 only. It was expected since the same soil profiles were studied and there is no significant difference between input motions.



Left: Figure 4. Target, original and matched spectra for seismic response analyses.

Right: Figure 5. Transfer functions (Output on surface and input motion ratio).

Figure 6 and 7 respectively present the comparison between elastic response spectrum, seismic amplification factor recommended by Peruvian Code and results obtained in the present study. NTP E.030 design spectrum corresponds to Soil Type 2, and the following parameters: $Z=0.4g$ (PGA), $U=1.0$ (use and importance coefficient for common buildings, e.g. houses), $T_P=0.6$ s (fundamental soil period), $S=1.2$ (soil factor), and C (seismic amplification coefficient) variable according to Equation 1 (see Figure 7) based on Meneses and Alva's work (1986). Table 3 summarizes seismic response analyses results.

$$C = 2.5 \left(\frac{T_P}{T} \right) ; C \leq 2.5 \quad (1)$$

where T_P and T stand for the fundamental soil period and structural period respectively.

This article results and Peruvian Code recommendations comparison show a general underestimation of spectral accelerations in seismic design spectra, which is mainly attributed to

Table 3. Seismic response analysis results summary.

Seismic Profile	Location	Soil Amplification Factor	Maximum Spectral Acceleration (g)	Structural Amplification Factor
A-02	San Clemente city (Right margin of Pisco River)	2.0 – 3.5 (0.20 – 0.50 s)	1.5 – 3.0 (0.10 – 0.40 s)	2.5 – 4.0 (0.12 – 0.40 s)
A-03	Santa Cruz (South-east study area)	2.0 – 3.5 (0.20 – 0.50 s)	1.5 – 3.0 (0.10 – 0.40 s)	2.5 – 4.0 (0.12 – 0.40 s)
A-04	Northern Santa Cruz (Paracas-San Andres boundary)	1.7 – 2.5 (0.09 – 0.15 s)	1.2 – 2.2 (0.08 – 0.35 s)	2.5 – 3.2 (0.09 – 0.22 s)
A-07	El Golf (In front of Paracas Bay)	2.0 – 4.0 (0.15 – 0.28 s)	1.5 – 3.5 (0.10 – 0.30 s)	2.5 – 4.5 (0.12 – 0.30 s)

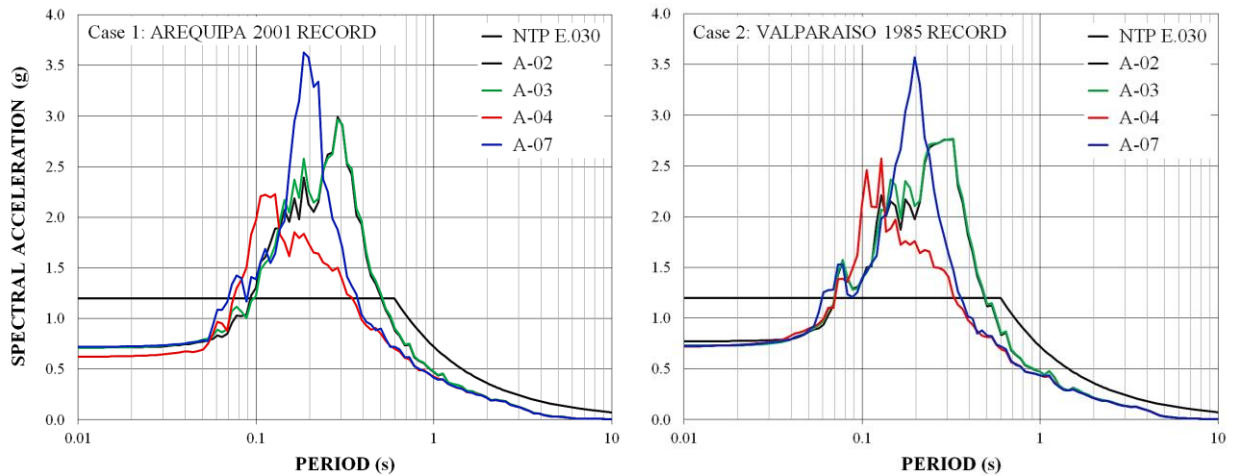


Figure 6. Seismic response spectra on surface and NTP E.030 seismic design spectrum.

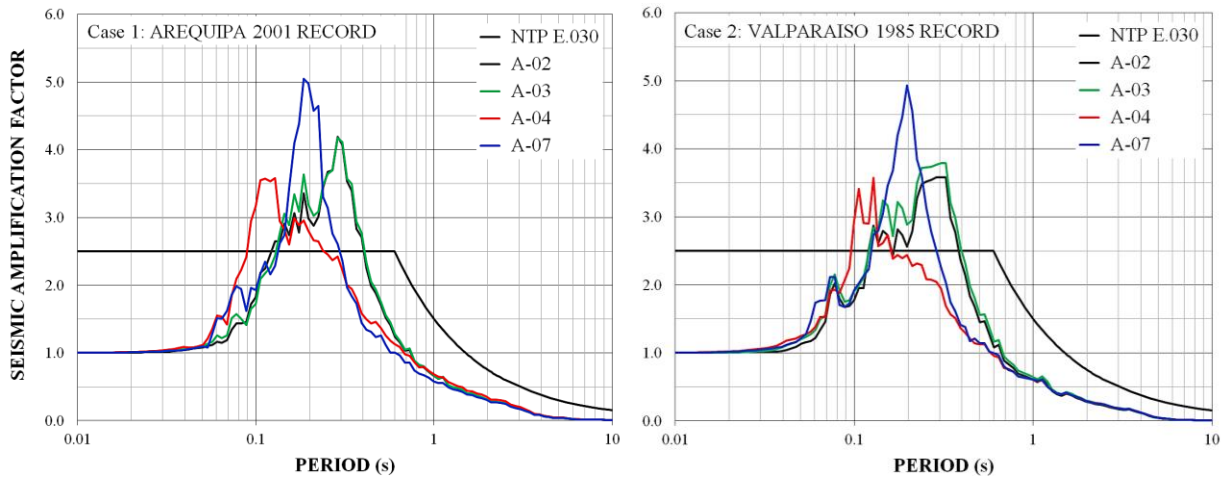


Figure 7. Normalized seismic response spectra on surface and NTP E.030 seismic amplification factor.

S parameter (soil factor) considered by NTP E.030. Results in Table 3 present soil amplification factors up to 1.7 until 4.0 while a value of 1.2 is recommended by Peruvian Code for S_2 profile type (intermediate soils).

Amplification factor spectrum suggested by E.030 reasonably envelopes results obtained in this paper at short periods. Seismic coefficient overestimation at long periods has been well recognized (Angulo et al., 2013) and should be change to decrease quadratically with period instead of linearly as current code suggest (Equation 1).

Seismic Microzonation

A flooding prone areas map (CISMID, 2012) due to tsunamis occurrence was integrated to studies previously described to develop a microzonation map for Pisco. Four zones were drawn in Figure 8 distributed in the study area as follows.

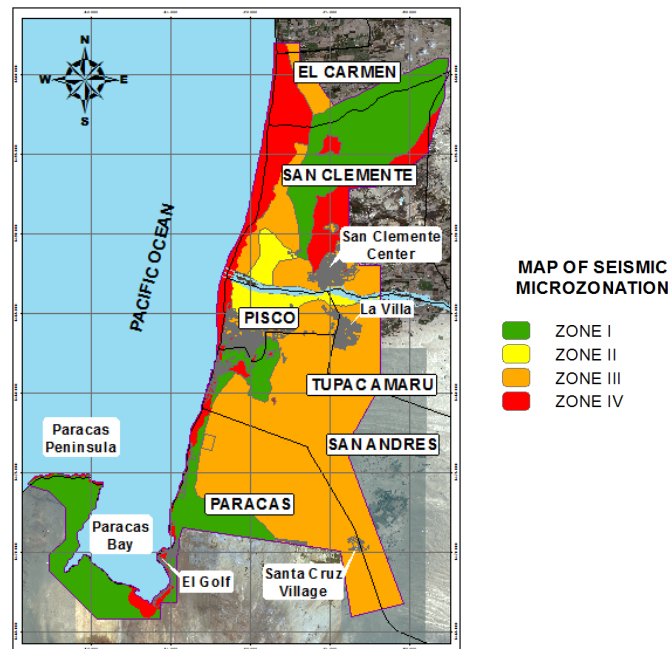


Figure 8. Map of Seismic Microzonation.

- Zone I, composed by rock formations located in Paracas peninsula, dense gravelly soils in San Andres and Paracas, dense silty sands in the northern coast of Paracas, as well as highly and medium dense sands found in El Carmen and San Clemente. Phreatic surface depth is found 1.5 m below surface. Fundamental period of soils are shorter than 0.1 s in Pisco and San Clemente, but longer than 0.15 s in San Andres and Paracas. Soil and structural amplification factors are presented in Table 3 corresponding to A-07 seismic profile.
- Zone II, silty sand deposits thinner than 1.5 m over an alluvial gravels deposit derived from Pisco River at both margins of Pisco River are included (see Figure 8). Phreatic level is located at 1.5 to 2.5 m depth. Fundamental periods of soils are shorter than 0.1 s.
- Zone III, conformed by silty sand thicker than 1.5 m and alluvial soils mainly located in San Andres and Paracas, but in minor extension in San Clemente Center, Tupac Amaru and Pisco. Outcrops of diatomite found in San Clemente and Pisco were also included due to plastic characteristics in wet conditions (PI from 30 to 55). Soil fundamental periods are

shorter than 0.1 s, but 0.20 to 0.30 exceptional cases. Seismic response analyses have shown two main trends presented in Table 3: (1) A-02 and A-03 cases and, (2) A-04

- Zone IV, comprises coastal marine deposits, potential liquefiable sands in El Carmen, and anthropogenic fills and wetland in various punctual areas of Pisco and San Andres (see Figure 2). Most of coast in the study area belong to this zone due to tsunami flooding risks.

Conclusions

1. Four zones were defined in correspondence to different levels of hazard for the study area conceptually related to NTP E.030 Peruvian Code zone classification. Zone I and II are considered to present the best conditions for settlement of communities after minor considerations, while major attention for Zone III; finally Zone IV is not recommended for cities establishment. Authorities should consider the use of this map of seismic microzonation as a reference in urban planning in the upcoming years in order to avoid human and material losses experienced in previous earthquake events.
2. According to seismic response analysis, it is expected that framed buildings with 1 to 3 floors or structures whose fundamental period fall inside a range from 0.10 to 0.30 s would mainly undergo spectral acceleration higher than 1.5g. Seismic response spectra presented in this article are recommended for design purposes for areas mentioned in Table 3, however further analyses are required for seismic response spectra zonation.
3. Differences between the obtained seismic response spectra and elastic seismic design spectrum (for common buildings category) recommended by Peruvian Code are mainly attributed to soil factor considered by NTP E.030, as well as the lack of earthquake stations and records available to develop design spectra for different site conditions for Peruvian and Chilean earthquakes.
4. SENCICO's tool for seismic hazard information presents an acceptable agreement with previous studies (Castillo and Alva, 1993, and Monroy et al., 2006), although different ground motion prediction equations were considered.
5. Further geotechnical and geophysical points of investigation are recommended including boreholes near microtremor measurements to correlate seismic profiles with geotechnical data.

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