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SEISMIC AMPLIFICATION IN TACNA-PERU, USING SEISMIC MOTION DATA AND ARRANGEMENTS OF MICROTREMOR

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Abstract

Tacna city in Peru is located within the area that includes the Pacific Ring of Fire, a zone of high seismic activity. According to its seismic history, earthquakes have been occurring in Tacna for the past five hundred years, causing the total destruction of the city on more than one occasion such as the 1868 earthquake which had a magnitude of Mw=9.0 and an intensity of X MMI (Modified Mercalli Intensity Scale). The most recent major seismic event took place on June 23rd, 2001 which recorded a magnitude of Mw=8.4. Most of the damage occurred in the districts of Ciudad Nueva and Alto de la Alianza which are built on loose sand deposits and volcanic deposits.

This research analyzes the ambient noise (microtremor) by applying the Nogoshi and Igarashi (1971) and Nakamura (1989) methods. It also analyzes eighty seismic records from six seismic stations located in the city of Tacna.

The S-wave velocity profile was estimated using the spatial autocorrelation (SPAC) method, and the bedrock is found at a depth of between 124 m and 306 m. The Vs30 values obtained were between 340 m/s to 600m/s and, according to the ASCE-7, the site is classified as Class C and Class D. The seismic records were analyzed through response spectra and were compared with response spectra obtained from non-linear site response analysis.

In addition, the fundamental period was obtained by four methods: microtremor H/V spectral ratio (HV-M), spectral ratio of seismic record (HV-S), transfer function from Equivalent-Linear analysis (TF-EL) and spectral ratio between soil spectrum to rock spectrum from the non-linear analysis (Soil/Rock-NL). The results show that the fundamental period of soil increases with the intensity of the seismic event with respect to value of period obtained from microtremor. This is due to the effects of nonlinear soil behavior.

According to the data, soil amplification values in Tacna, vary from 1.3 to 1.6. The fundamental period for site Class D varies from 0.34 s to 0.37 s, based on the EL method, and from 0.75 s to 0.80 s based on the NL method, while for site Class C the fundamental period varies from 0.15 s to 0.30 s, based on the EL method, and from 0.19 s to 0.34 s, based on the NL method. The acceleration response spectra show that the values of the amplification coefficients vary from 3.2 to 3.5. These results are greater than such values proposed by the Peruvian Seismic Design Code E.030.

Keywords: Microtremor; seismic motion; spectral ratio.

1. Introduction

Peru is located in a seismic hazard zone given the interaction of the Nazca and South American Plate, as well as the activity of surface geological faults which also generate earthquakes of considerable magnitude in the interior of the continent. A spatial analysis of the seismicity shows a notable decrease in the frequency of occurrence of earthquakes off the coast of the departments of Lima, Moquegua and Tacna, which suggests that in these areas energy is accumulating and will be released at some point in time [1] as shown in Fig. 1a.

Seismic events frequently cause an increment in acceleration on ground surface, compared to bedrock acceleration, or amplification of seismic wave, and generate seismic forces in structures, causing considerable material damage and human loss in recurrent manner to vulnerable buildings.

For this research, we collected information from other related researches in Tacna, such as Cortez [2], Yamanaka et al. [3], Pulido et al. [4] among others.

The study area is located in the south of Peru, specifically in the city of Tacna. Field works and microtremor measurements were carried out at the accelerograph stations located in the districts of Ciudad

Nueva (MCN[1] and SENCICO[2]), Pocollay (UPT[1]), Tacna (UNJBG[1]), Alto de la Alianza (UNJBG-A[2]) and Calana (CIP CALANA[3]). The location of the stations are shown in Fig. 1b.

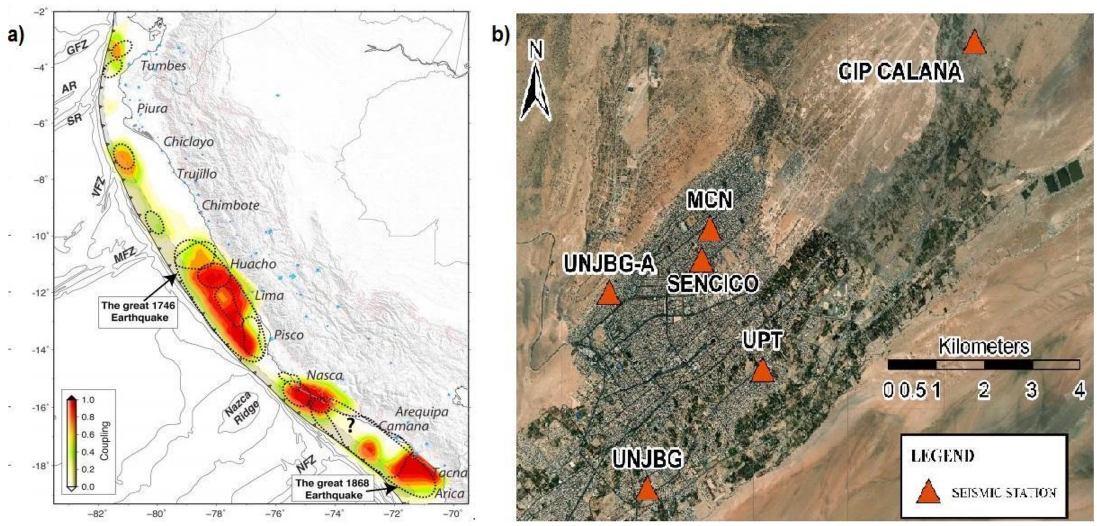

Fig. 1 – a) Zones of accumulating energy [1]. b) Location of Seismic Stations

2. Methodology

In order to calculate seismic amplification, the ground motion caused by the seismic events and the environmental noise recorded by microtremors were obtained. Then the spectral ratio of both movements was analyzed to determine the predominant frequency (period). Site response analysis was also performed to observe seismic amplification based on onsite and input rock motion geotechnical characteristics. The methodology for assessing seismic amplification is shown in Fig. 2.

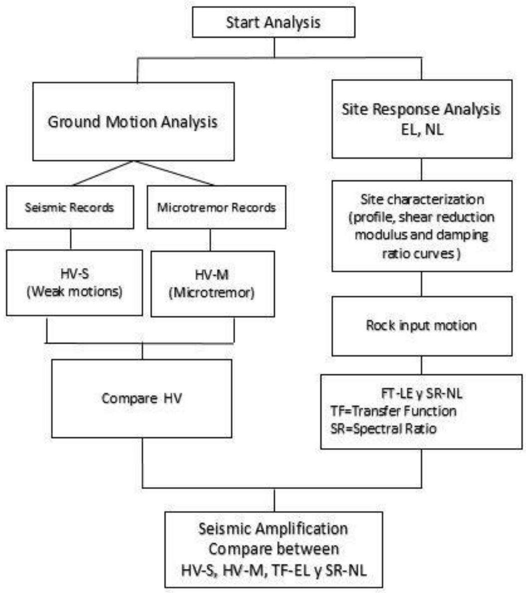

Fig. 2 – Methodology to perform Seismic Amplification Analysis

[1] Japanese-Peruvian Center for Seismic Research and Disaster Mitigation (CISMID-UNI) Accelerogram network

[2] Postgraduate of Faculty of Engineering (FIC-UNI) Accelerogram network

[3] Peruvian Association of Engineers -National Board (CIP-CN) Accelerographic network

3. Conditions of Soil in Tacna

3.1 Geology of Tacna

Tacna's geomorphology consists of Pampa Costera and the Valley subunit. The Tacna valley was formed during the Pleistocene, but the regional geological formation comprises from the Cretaceous to the Holocene Quaternary. The in-depth stratigraphic sequence of the Caplina river valley, which crosses the city of Tacna, is made up as follows: first level of fluvial-alluvial deposits, second level of volcanic ash formed by pumice stone, third level of ancient conglomerates, and below, the old basement [5], as shown in Fig. 3.

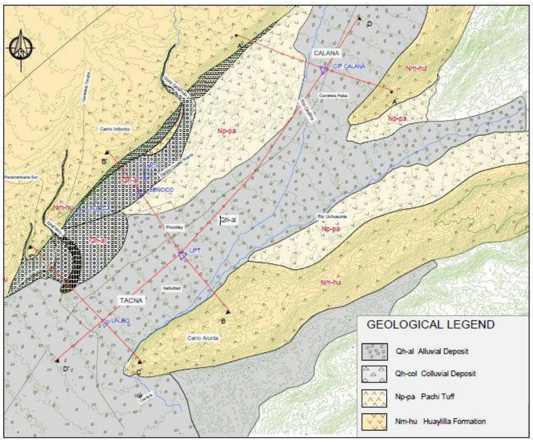

Fig.3 –Geology of Tacna

3.2 Geotechnical Characteristics

For this study, sixty-seven surveys corresponding to test pits [6] and five SPT penetration tests [2] were considered. They recorded the characteristics of the soil, allowing to classify them using the Unified Soil Classification System (SUCS) and identifying two predominant types of soils: gravelly, in the districts of Tacna, Pocollay and Calana, and silty sand, in the districts of Alto de la Alianza and Ciudad Nueva, as shown in Fig. 4. We estimated the gravel deposits to have a thickness of 15 m while the sand deposits a thickness of 8 m. Below the predominant soils there is a second layer of pink volcanic ash, and below that a third layer composed of Ancient conglomerates. Finally, there is underlying bedrock (the Moquegua Formation).

Also, in the area where the UNJBG-A accelerograph station (Alto de la Alianza District) is located, there is an almost superficial presence of volcanic rock formed by extremely fractured volcanic tuffs.

Fig. 4 – Gravelly and Sandy soil in Tacna City, respectively.

3.3 Geophysical Tests in Tacna City

The soil dynamic behavior of the accelerograph stations was determined by analyzing Multichannel Analysis of Surface Waves (MASW) measurements [7], as well as microtremors measurements and microtremors arrangements through the SPAC [8]. The number of performed tests were: 25 MASW tests, 5 microtremor arrangements to obtain the S-wave velocity profiles (Vs), and 92 microtremor measurements to obtain the fundamental period of soil (T).

The velocity profiles show values of V_{s30} between 340 m/s and 600 m/s and are classified according to the ASCE 7-16-2016 [9] Code as C and D. Furthermore, with the microtremor essays and the spectral rate analysis, the vibration period of soils was obtained and found to vary from 0.15 s to 0.34 s [10].

4. Ground Motion Analysis in Soils

4.1 Seismic Records

Fourteen seismic events with accelerations greater than 10 gals at each accelerograph station in the city of Tacna were analyzed, obtaining a total of 84 seismic records. For the purpose of analysis and verification of the acceleration values obtained from the site response analysis, three historical seismic events that occurred in the southern and central regions of Peru were considered, namely, the Ocoña earthquake (Mw = 8.4) on June 23rd, 2001, recorded by the Arica Casa Station (ARI) in Chile [2]; the Pisco earthquake on August 15, 2007 (Mw = 7.9) recorded by the Parcona Station (PARC), and the Cañete earthquake on October 3rd, 1974 recorded by Parque de la Reserva Station (PQR). Seismic events are shown in Table 1.

Table 1 – Seismic Events

No.	Date	Mag	Intensity(MM)	Lat(°)	Lon(°)	Depth (Km)
1*	1974/10/03-09:21:00	8.1 Mw	VIII Lima	-12.07	-77.04	21
2*	2001/06/23-15:33:00	8.4 Mw	VII-VIII Arequipa, Moquegua y Tacna	-16.08	-73.77	33
3	2003/08/26-16:11:35	5.7 Mw	-	-17.16	-70.67	31.6
4	2004/01/27-11:00:37	5.8 Mw	-	-17.84	-71.07	56.9
5	2004/11/09-13:00:54	4.6 mb	-	-17.53	-70.21	81.5
6	2005/04/16-17:41:16	5.8 Mw	III Arica	-17.65	-69.66	118.7
7	2005/04/20-05:40:47	4.9 Mw	-	-17.58	-71.35	28.1
8	2005/07/13-07:06:13	5.9Mw	IV Tacna	-17.85	-70.11	79.9
9*	2007/08/13-18:40:58	7.9Mw	VII Pisco, Chincha, Cañete	-13.36	-76.52	30.2
10	2010/05/05-21:42:47	6.2 Mw	VII Tarata, Tacna, Peru	-18.06	-70.55	37
11	2012/05/14-05:00:40	6.2 Mw	VII Iquique, Tarapacá, Chile	-17.68	-69.59	105.9
12	2014/04/01-18:46:47	8.2 Mw	IX Iquique, Tarapaca, Chile	-19.61	-70.77	25
13	2014/04/02-21:43:13	7.7 Mw	VIII Iquique, Tarapacá, Chile	-20.57	-70.49	22.4
14	2015/03/22-23:51:48	6.4 Mw	V Iquique, Tarapaca, Chile	-18.35	-69.17	130

* Seismic record used to compare with the results of the site response analysis

4.2 Spectral Ratio of Seismic Records

The spectral ratio (HV) was calculated using the Fourier amplitude spectrum, which is the original method studied by Nogoshi and Igarashi [11] for Rayleigh waves. The spectral ratio procedure was performed using the Root Mean Square method proposed by Nakamura [12]. The HV spectrum allows to identify the fundamental or peak period (frequency) by the amplification of the soil with respect to bedrock. Predominant period values by each station are shown in Table 2, and HV spectra of the seismic records (HV-S) for MCN and UNJBG stations are shown Fig. 5, respectively.

Table 2 – Values of predominant period obtained from HV of earthquakes (HV-S)

N°	Seismic station	Class Site (ASCE-7)	Period (s)
1	UNJBG	C	0.24
2	UPT	C	0.27
3	MCN	D	0.33
4	SENCICO	D	0.32
5	CIP CALANA	C	0.20
6	UNJBG A	C	0.15

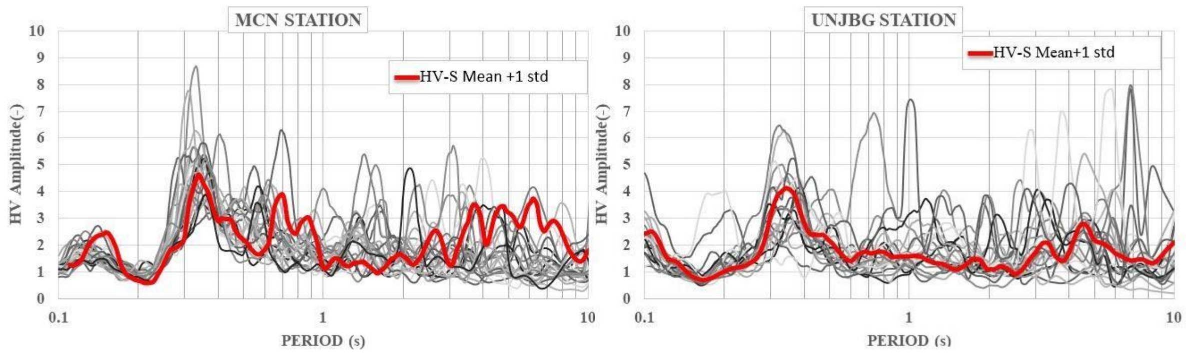

Fig. 5 – Spectral ratio of seismic records, from MCN and UNJBG stations

4.3 Microtremor Records

Ninety-two (92) microtremor measurements were taken in the city of Tacna, five of which correspond to measurements by accelerograph stations. For those measurements, McSEIS-NEO equipment was used. The spectral ratio procedure was performed using the Root Mean Square method (HVM-RMS) [12] and directional spectral densities (HVM-SD) [13]. The HV-M spectrum was performed with the aid of the Microtremorsoft program [14]. Table 3 shows the fundamental period values from HV-M spectra for each station. The HV-M spectra, which were obtained with both methods for the MCN and UPT stations, are shown in Fig. 6. The fundamental period is the same while the amplitudes differ, giving higher amplitude values with the spectral density method (HVM-SD).

Table 3 – Values of predominant period from HV of microtremors (HV-M)

N°	District	Station	Lat (°)	Lon (°)	Period (s)
1	Pocollay	UPT	-18.005	-70.226	0.24
2	Ciudad Nueva	MCN	-17.983	-70.237	0.30
3	Ciudad Nueva	SENCICO	-17.988	-70.238	0.27
4	Calana	CIP CALANA	-17.953	-70.184	0.15
5	Alto de La Alianza	UNJBG A	-17.993	-70.256	0.15
6	Tacna	UNJBG	-18.024	-70.249	0.18

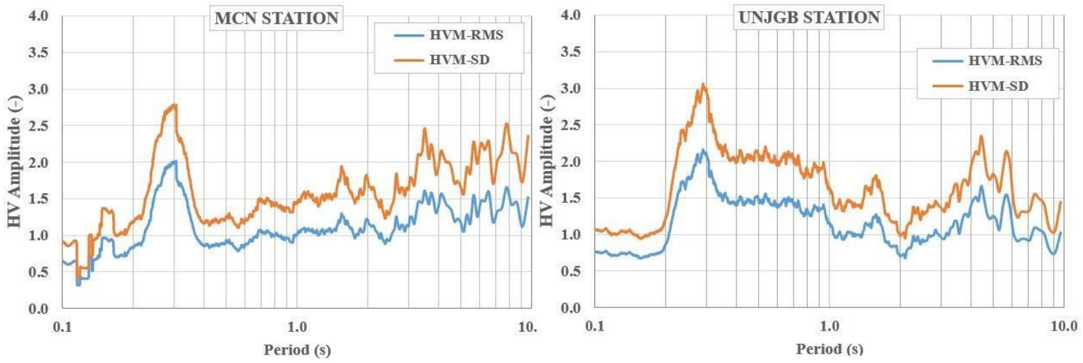

Fig. 6 – Spectral ratio of microtremors records, from MCN and UPT stations

5. Site Response Analysis

5.1 Soil Profile

The subsoil profiles of the accelerograph station used for the site response analysis were obtained by microtremor array analysis using the Spatial Autocorrelation method (SPAC) [8] and combining the results of geotechnical tests, geophysical tests and geology. The S-wave velocity profile was estimated down to bedrock, the depth of which is between 124 m to 306 m, as shown in Fig.7. The S-wave velocity for each station are shown in Table 4.

Table 4 – S-wave velocity value by seismic station

UNJBG		**UPT**		**CIP CALANA**		**UNJBG A**		**MCN**		**SENCICO**	
H (m)	**Vs (m/s)**	**H (m)**	**Vs (m/s)**	**H (m)**	**Vs (m/s)**	**H (m)**	**Vs (m/s)**	**H (m)**	**Vs (m/s)**	**H (m)**	**Vs (m/s)**
4	390	7	465	10	450	7	395	1.5	180	9	265
12	568	9	590	10	500	7	500	3	219	12	351
14	688	30	758	16	600	17	650	6.5	350	9	489
36	900	20	900	40	850	22	750	20	410	20	550
110	1074	110	1074	50	900	23	873	77	770	74	770
-	1200	-	1200	80	950	64	1100	16	871	-	1200
				100	1049	-	1200	-	1200		
				-	1200						

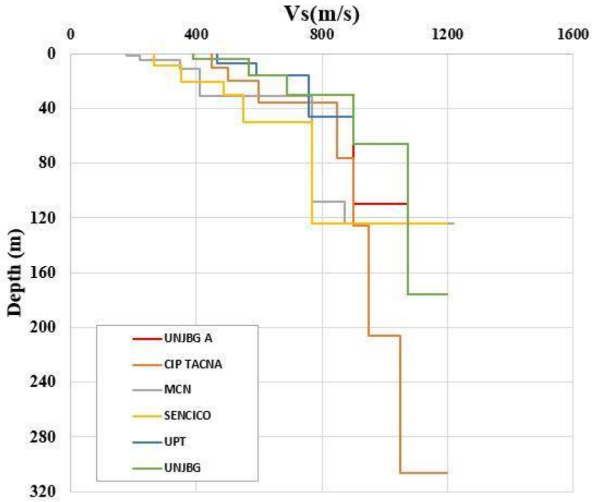

Fig. 7 – S-wave velocity profile.

5.2 Input Rock Motion

Given that there is no seismic rock motion in the city of Tacna, an input rock motion was established based on a synthetic time series and by applying the spectral adjustment method [15], using a uniform hazard spectrum (UHS). The UHS was obtained from a probabilistic seismic hazard analysis following Cornell's methodology [16], using subduction and crustal sources, as well as the seismic recurrence parameters of each source proposed by Gamarra and Aguilar [17] and the ground motion prediction equation for rock, for subduction earthquakes and crustal sources proposed by Young et al. [18] and Sadigh et al. [19], respectively. The seismic record from Arica Casa Station was modified to create the synthetic accelerogram with a PGA of 0.31g. The synthetic accelerogram and its corresponding spectrum adjusted to UHS are shown in Fig. 8.

5.3 Dynamic Properties of Soil

The dynamic behavior of soil against a cyclic load is obtained by the stress-strain curve, the behavior of the soil can be represented by the shear modulus reduction (G/Gmax) and damping (ξ) curves. For the sand and gravel soils of Tacna city, the maximum, minimum confinement stress were calculated, and the empirical relationships proposed by Menq [20] and Zhang et al. [21] respectively were used in order to compare them with the G/Gmax and ξ curves proposed by Seed et al. [22], as shown in Fig.9.

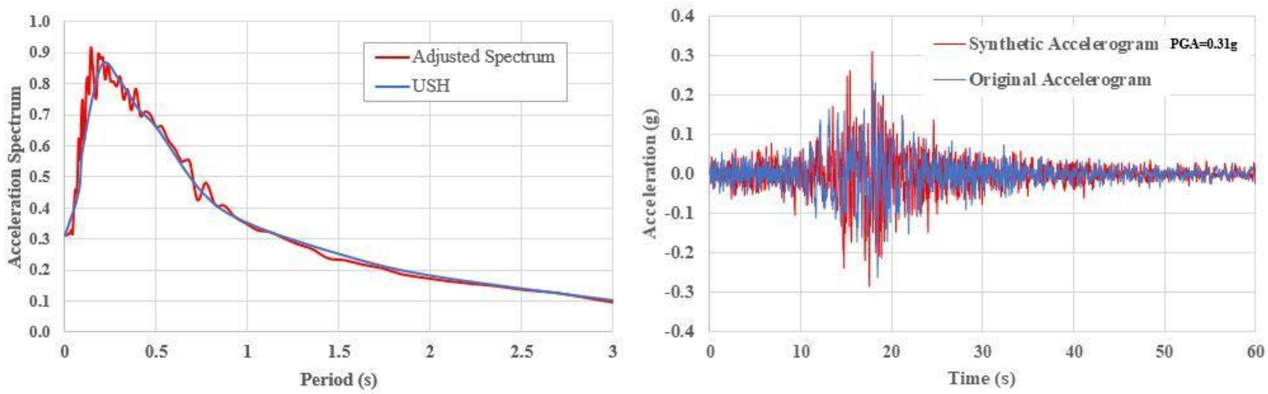

Fig. 8 – (Left.) Real and synthetic accelerogram. (Right) Uniform hazard spectrum and adjusted spectrum

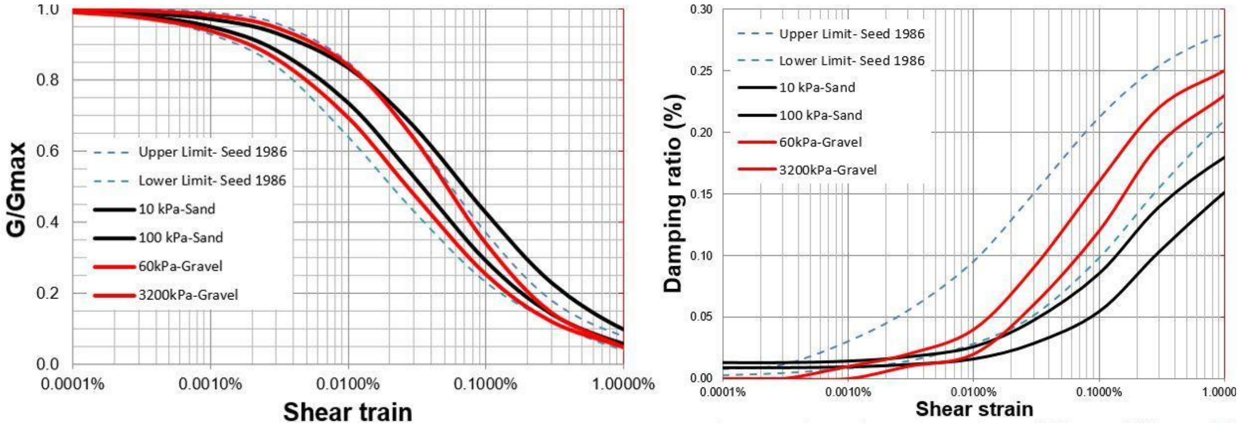

Fig. 9 – Shear modulus reduction and damping ratio curves for sandy and gravelly soil of Tacna

5.4 Site Response – Equivalent Linear and Non Linear

The site response of a soil deposit is based on the assumption that superficial soil layered are horizontal, and the vertical propagation of the SH waves is predominant [23]. Kelvin-Voigt model was used as the model of soil, and the analyses were done with Deepsoil computer program [24]. The results of Equivalent Linear analysis show that, on the ground surface the maximum acceleration mean for site Class C (V_{s30} = 510 - 600 m/s; UNJBG, UPT, UNJBG-A and CIP CALANA stations) and site Class D (V_{s30} = 340 to 350 m/s, MCN and SENCICO stations) are 0.40g and 0.51g, respectively; and the amplifications of the accelerations in the ground with respect to the rock are 1.30 and 1.80, respectively. The elastic response spectra for the 5% damping and the Transfer Function of each of the profiles were also obtained, as shown in Fig. 10.

For the non-linear analysis, the dynamic parameters of the soil were used for discretizing each stratum of the profiles in substrata, considering that the frequency of vibration of the substrata is greater than 25 Hz [24]. The model of soil was MKZ and Non-Linear analyses were performed by Deepsoil software. The results were the acceleration response spectrum and seismic amplifications in each accelerograph station. From the results, it can be seen that on the ground surface, the average maximum accelerations for site Class C (UNJBG, UPT, UNJBG-A and CIP CALANA stations) and site Class D (MCN and SENCICO stations) are 0.38g and 0.46g respectively and the maximum peak acceleration amplifications with respect to the rock are 1.30 and 1.60, respectively. In addition, the normalized response spectra show that the structural amplification coefficients vary from 3.2 to 3.5, as shown in Fig. 11. These values are larger than the structural coefficients (values of 2.5) of the Peruvian Seismic code E030.

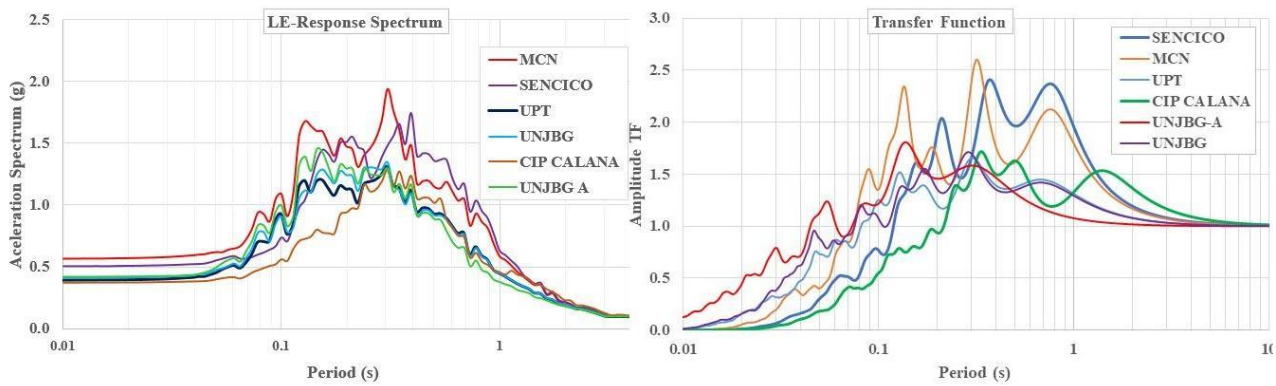

Fig. 10 – Acceleration Spectrum and Transfer Function, Linear-Equivalent Analysis

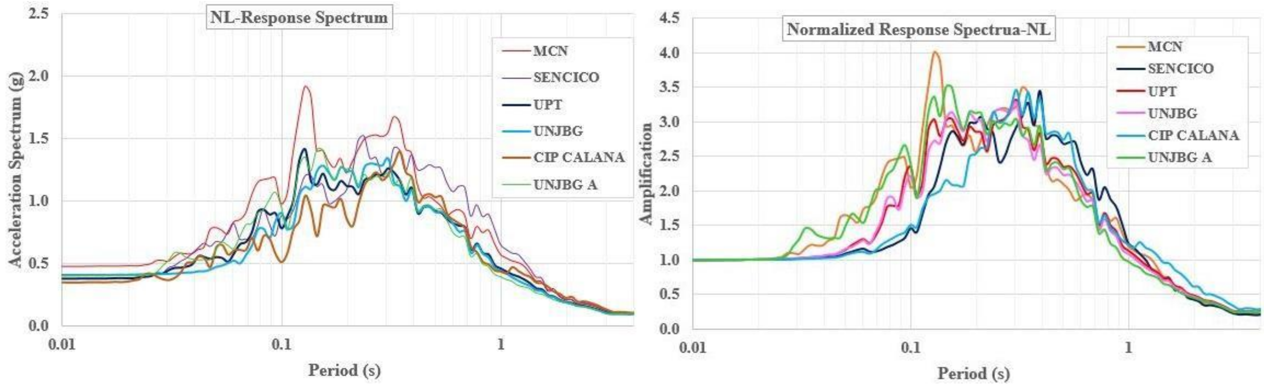

Fig. 11 – Acceleration Spectrum and normalized acceleration Spectrum, Non-Linear Analysis

6. Discussion of Results

6.1 Fundamental Period of Soil

With respect to the periods, results of the study area were compared by four different methods: microtremor H/V spectral ratio (HV-M) records, spectral ratio of seismic (HV-S) records, transfer function from Linear-Equivalent (TF-LE), and the spectral ratio between soil spectrum to rock spectrum (Soil/Rock-NL) obtained from nonlinear analysis. Fig. 12 shows the results for UPT and SENCICO stations.

For site Class C, the peak periods obtained by HV-M and HV-S are similar, while for site Class D (Table 5 and Fig. 12) peak values are different; with respect to peak period values obtained from FT-LE spectrum and Soil/Rock-NL spectrum, Class C has similar values; however, comparing the two latter peak periods with the periods obtained by HV-M and HV-S, spectra turn out to be larger, and this is due to the effect of the nonlinearity of the soil, observing that the peak period values are higher for earthquakes of greater magnitude with respect to the values obtained by microtremors. Based on the results obtained by the site response analysis, it is also evident that the rigidity of the material is reduced, behaving like flexible material.

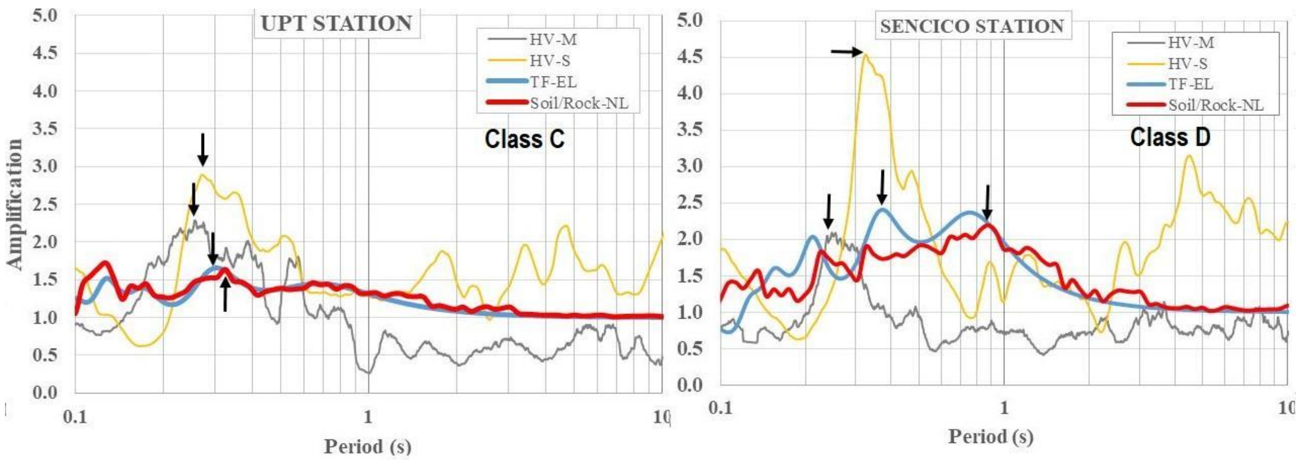

Fig. 12 – Comparison of the period and amplification between the HV-M, HV-S, FT-LE and Soil/Rock-NL for Class C and Class D.

Table 5 – Predominant Period Values, obtained from the earthquake

N	Station	Class Site	Average Period (s)			
			HV-M	HV-S	TF-LE	Soil/Rock NL
1	UNJBG	C	0.18	0.24	0.29	0.30
2	UPT	C	0.24	0.27	0.30	0.34
3	MCN	D	0.30	0.33	0.34	0.75
4	SENCICO	D	0.27	0.32	0.37	0.80
5	CIP CALANA	C	0.15	0.20	0.30	0.34
6	UNJBG A	C	0.15	0.15	0.15	0.19

6.2 Soil Amplification

From the soil response analyses (LE and NL), it is clear that, on the surface, the maximum amplifications of the soil with respect to the rock are larger for site Class D than for site Class C, as seen in Table 6 and in Figs. 10 and 11.

In addition, the response spectra in soil were compared with the response spectra obtained in rock to determine the amplifications (as Soil/Rock-NL) with respect to short periods (0.15 s to 0.5 s), intermediate periods (0.5 s to 1.5 s) and long periods (1.5 s to 5.00 s) as shown in Table 7; appreciating that for site Class C for short periods amplifications vary from 1.28 to 1.48 on average, for intermediate periods amplifications vary from 1.24 to 1.37 on average and for long periods amplification factors vary from 1.03 to 1.24. For site Class D it is observed that for short periods amplifications vary from 1.54 s to 1.94 s on average, for intermediate periods amplifications vary from 1.66 s to 1.92 s on average and for long periods amplification factors vary from 1.19 to 1.23.

Table 6 - Soil amplifications with respect to rock

Station	Class Site	PGA (g)		Amplification (soil over rock)	
		EL	NL	EL	NL
UNJBG	C	0.41	0.41	1.3	1.3
UPT	C	0.39	0.38	1.3	1.3
MCN	D	0.57	0.49	1.8	1.6
SENCICO	D	0.51	0.42	1.6	1.4
CIP CALANA	C	0.37	0.34	1.2	1.1
UNJBG A	C	0.42	0.40	1.3	1.3

Table 7. Comparison of soil amplification values based on short, intermediate and long periods.

Range of period (s)		MCN	SENCICO	UPT	UNJBG	CIP CALANA	UNJBG A.
0.10 s to 0.5 s	Min	1.39	1.16	1.24	1.25	0.78	1.25
	Max	2.41	1.92	1.72	1.63	1.78	1.64
	Average	**1.90**	**1.54**	**1.48**	**1.44**	**1.28**	**1.44**
0.5 s to 1.5 s	Min	1.44	1.65	1.27	1.20	1.20	1.07
	Max	1.89	2.20	1.46	1.42	1.56	1.41
	Average	**1.66**	**1.92**	**1.37**	**1.31**	**1.38**	**1.24**
1.5 s to 4 s	Min	1.02	1.02	1.01	1.00	1.03	1.00
	Max	1.37	1.45	1.16	1.13	1.45	1.06
	Average	**1.19**	**1.23**	**1.08**	**1.07**	**1.24**	**1.03**

7. Conclusions

Using seismic records, microtremor measurements and site response analyses (EL and NL), the seismic amplification of the soil in Tacna was classified as Class C and Class D. The values obtained for the acceleration soil amplification with respect to bedrock were 1.3 and 1.6 for sites Class C and Class D, respectively; and values of structural amplification coefficients vary between 3.2 to 3.5, larger than the structural amplification factor (value of 2.5) of the Peruvian Seismic Code E.030.

The peak periods of the study area were determined by four methods: Microtremor H/V spectral ratio (HV-M) record, spectral ratio of the seismic (HV-S) records, the transfer function obtained from the linear equivalent analysis (FT-LE) and the spectral ratio between soil spectrum to rock spectrum from the non-linear analysis (Soil/Rock-NL), concluding that the increment in peak period values for earthquakes of larger magnitude with respect to peak period values obtained by microtremors measurements are due to the effect of soil nonlinearity.

The response spectra in soil and in rock (NL) were compared to evaluate amplifications with respect to short periods (015 s to 0.5 s), medium periods (0.5 s to 1.5 s) and long periods (1.5 s to 5.00 s). Based on the results, it can be observed at site Class C, amplifications vary in period range from 1.28 s to 1.48 s; 1.24 s to 1.37 s and 1.03 to 1.24, respectively. With respect to site Class D, amplifications vary from 1.54 s to 1.94 s; 1.66 s to 1.92 s and 1.19 to 1.23, respectively.

5. Acknowledgment

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6. References

[1] Villegas-Lanza J, Chlleh M, Cavalle O, Tavera H, Baby P, Chire-Chira J y Nocquect M (2016): *Active Tectonics of Peru: Heterogeneous interseismic coupling along the Nazca megathrust, rigid motion of the Peruvian Sliver, and Subandean shortening accommodation*. Journal of Geophysical research, Solid Earth, 121 (10), USA.

[2] Cortez A (2004): *Site Response of the 2001 Southern Peru Earthquake*. Master of Science in Civil Engineering. Washington State University.

[3] Yamanaka, H., Quispe, M, Chimoto, K., Saguchi, K.,Calderon,D. y Lazares F. (2014).*Exploration of deep sedimentary layers in Tacna city, southern Peru, using microtremors and earthquake data for estimation of local amplification*. Journal of Seismology, ISSN 1383-4649, **20** (1), Japan.

[4] Pulido N, Nakai S, Yamanaka H, Calderon D, Aguilar Z, Sekiguhi T (2014): *Estimation of a Source Model and Strong Motion Simulation for Tacna City, South Peru*, Journal of Disaster Research, 9 (6).

[5] Cabrera F. (2018): Geology Studies in the City of Tacna. Formative Research Project. FIC-F-3-2018. National University of Engineering, Lima, Peru (in Spanish).

[6] Ortiz C. (2010). *Project of Seismic intensity distribution measuarements in Tacna City using Seismoscope*. Posgraduate Thesis. National University of Engineering, Lima, Peru (in Spanish).

[7] Alva J, Ortiz C, Huanacuni D (2015): *Dynamic Characteristics of Soil in Tacna City*. 19th National Congress of Civil Engineering. Huaraz, Peru (in Spanish).

[8] Aki K (1957): *Space and Time Spectra of Stationary Stochastic Waves, with Special Reference to Microtremors*, Bulletin Earthquake Research Institute, Tokyo University, 25, 415-457.

[9] ASCE 7 (2016): *American Society of Civil Engineering. Minimum Design Loads and Associated Criteria for Building and Others Structures*. USA.

[10] Alva J, Ortiz C (2018). *Formative Research Project. Technical Report.* National University of Engineering, Lima, Peru (in Spanish).

[11] Nogoshi M, Igarashi T (1971): *On the amplitude characteristics of microtremor (part 2)*. of Seism. Soc. of Japan, 24, 26-40

[12] Nakamura Y (1989): *A Method for Dynamic Characteristics Estimation of Subsurface using Microtremor on the Ground Surface*. Quarterly Report of Railway Technical Research Institute (RTRI), 30 (1)

[13] Sánchez-Sesma F, Rodriguez M, Iturraran-Viveros U, Luzon F, Campillo M, Margerin L, García-Jerez A, Suarez M, Santoyo M, Rodriguez-Castellanos A (2011): *A theory for microtremor H/V spectral ratio: application for a layared medium*. Geophys.J.Int.186, 221-225.

[14] Alva J, Ortiz C, Valverde J, Chipana M, Soto J, Diaz D, Tenorio A (2019): *MicrotremorSoft Manual*. Acelerographic Network UPG FIC UNI (in Spanish).

[15] Lilhanand K, Tseng W (1988): *Development and application of realistic earthquake time histories compatible with multiple damping response spectra*. Ninth World Conference Earthquake Engineering, 2, 819-824, Tokyo, Japan.

[16] Cornell C (1968): Engineering Seismic Risk Analysis. *Bulletin of Seismology Society of America*, (58), 1583-1606

[17] Gamarra C, Aguilar Z (2009): *New Seismic Source to Seismic Hazard Analysis and Uniform Response Spectrum in Peru* (In Spanish). CISMID, UNI, Lima, Peru (in Spanish).

[18] Youngs R, Chiou S, Silva W, Humphrey J (1997): *Strong Ground Motion Attenuation Relationships for Subduction Zone Earthquakes*. Seismological Research Letters, 68 (1).

[19] Sadigh K, Chang C, Egan J, Makdisi M, Youngs R (1997): *Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data*. Seismological Research Letters, BSSA, 68 (1).

[20] Menq F (2003): *Dynamic Properties of Sandy and Gravelly soils*. Doctoral Thesis. University of Texas.

[21] Zhang J, Andrus R, Juang H (2005): *Normalized shear modulus and material damping ratio Relationships*. Journal of Geotechnical and Geoenvironmental Engineering, 131 (4).

[22] Seed H, Wong R, Idriss I, Tokimatsu K, (1987): *Moduli and Damping Factors for Dynamic Analyses of Cohesionless Soils*, Journal of Geotechnical and Geoenviromental Engineering, 112 (11).

[23] Kramer S (1996): *Geotechnical Earthquake Engineering*. Ed. Prentice Hall. 2nd edition.

[24] Hashash Y, Musgrove M, Harmon J, Groholski D, Phillips C, Park D (2016): *DEEPSOIL 6.1, User Manual*.

