BI-DIMENSIONAL DYNAMIC ANALYSIS OF SEISMIC AMPLIFICATION IN THE ARCHAEOLOGICAL PARK OF SACSAYHUAMAN - CUSCO

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Abstract:

The research was developed in the Archaeological Park of Sacsayhuamán considered as Cultural Heritage of Peru, located in the Department of Cusco. In 2009, there were notable damages in the walls of the third terrace in the central part, some walls collapsed. The investigation presents the evaluation of the dynamic response of soils within the Sacsayhuamán Archaeological Park, using two-dimensional models and the finite element technique. This analysis allows to define the seismic behavior in terms of the seismic amplification product of the existing stratigraphy and topography.

The objective is to analyze the seismic amplification in the terrain surface of the different sections raised in the study area; For this purpose, two representative sections of the stratigraphic profile and the geometric conditions were selected.

Non-destructive techniques were used by geophysical tests using the methods of Multichannel Surface Wave Analysis (MASW), Seismic Refraction, Microtrepidation Measurement in Multichannel Arrays (MAM), as well as the Nakamura technique for fundamental period studies. Rehearsal were also conducted with Georadar (GPR).

Two-dimensional analysis was performed using Quake/W package of Geo-Slope International. Also, the accelerograph record of the earthquake occurred in Cusco on September 27, 2014, to generate a synthetic accelerogram, adjusted to a uniform hazard spectrum calculated from a study of Seismic Hazard and that has a maximum acceleration in rock of 0.25g, corresponding to a return period of 475 years.

According to the Geological - Geotechnical and Geophysical characteristics, in each section a soil stratum (clay with gravel) was defined with periods that are within the range of 0.35sec to 0.57sec; Under which is found massive rock (Limestones and Diorites). Based on the velocity of propagation of shear waves (Vs) and the Unit Weight, the Maximum Shear Module (Gmax) values were obtained for each stratum. The analysis was performed using the two-dimensional Equivalent Linear Method (Seed and Idriss, 1969), using the Shearing Module Reduction factors for soil and rock, with amplifications within the range of 1.1 to 1.6.

Also, the Fourier spectral ratio of the surface register and the rock record were determined to obtain the period of soil vibration and this was compared with the period of vibration found by microtremor measurement. Finally the corresponding spectral accelerations (with a damping factor of 5%) were obtained.

Keywords: Sacsayhuaman, Seismic Amplification, Geophysics, Linear Equivalent Method.

1. Introduction

The Archaeological Park of Sacsayhuamán is considered as Cultural Heritage of Peru. It is located in the Department of Cusco. In 2009 damage occurred in the walls of the third terrace of the Sacsayhuamán Fortress, in the central part some walls collapsed, it is assumed that the main cause was the lateral thrust caused by the addition of hydrostatic pressure due to water seepage product of the precipitations in addition to the presence of seismic movements (Photos N° 01 and N° 02).

The research has focused on the evaluation of the dynamic response of soils within the Sacsayhuamán Archaeological Park, using two-dimensional models and the finite element technique, with non-destructive techniques through geophysical tests to define soil parameters. The purpose is that the results can be used to prevent damage to the walls of existing terraces in seismic events and propose alternative solutions.

2. Objectives:

The main objective is to analyze the seismic amplification in the terrain surface of the different sections raised in the study area.

Photography N ° 01: View of the Study Area.
Source: Prepared by Richard Miksad[1]

Photography N ° 02: Inca wall is collapsed.
Source: Prepared by Richard Miksad[1]

3. Geophysical tests

The geophysical research was carried out in three stages corresponding to the months of July 2015, June 2016 and July 2017, in these three stages the following tests were executed: 62 lines of Seismic Refraction with a total length of 2057 meters, 16 MASW 1D test points and 6 MASW 2D test lines, 11 linear arrays MAM, through which the compressional and shear wave velocities (P waves and S waves) were determined, defining the power of the strata that make up the terrain on which Is the Archaeological Park of Sacsayhuamán. Also, 64 research points have been made forming a grid of lengths of 20 and 100 m, to estimate the fundamental period of the soil and 373 GPR lines with a total length of 8865 meters.

The location of the tests was defined according to the topography, geology, the layout of Inca wall areas and the available free area in the Sacsayhuamán area, allowing to cover the entire study area as shown in Figures N°01 to 06. Table No. 01 shows in summary the number of tests performed in the different stages.

Table N ° 01. Summary of Rehearsals.

ETAPAS	FECHA	REFRACCIÓN SÍSMICA		MASW		MAM		GEORADAR (GPR)		MICROTREMORES
		NRO. DE LÍNEAS	LONGITUD (M)	NRO. DE PUNTOS	LONGITUD (M)	NRO. DE PUNTOS	LONGITUD (M)	NRO. DE LÍNEAS	LONGITUD (M)	NRO. DE PUNTOS
PRIMERA ETAP	JUNIO DE 2015	32	977	4	218	1	100	135	2239	-
SEGUNDA ETA	JUNIO DE 2016	30	1080	12		-		25	838	-
TERCERA ETAF	JULIO DE 2016	-	-	6	255	10		213	5788	64
TOTAL		**62**	**2057**	**22**	**473**	**11**		**373**	**8865**	**64**

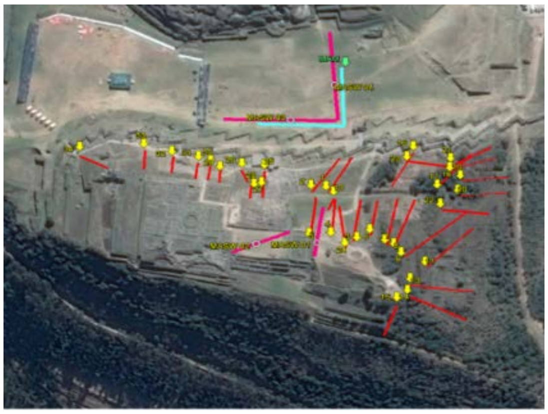

Figure N ° 01: View of geophysical tests carried out in the first stage.

Figure N ° 02: View of GPR tests carried out in the second stage.

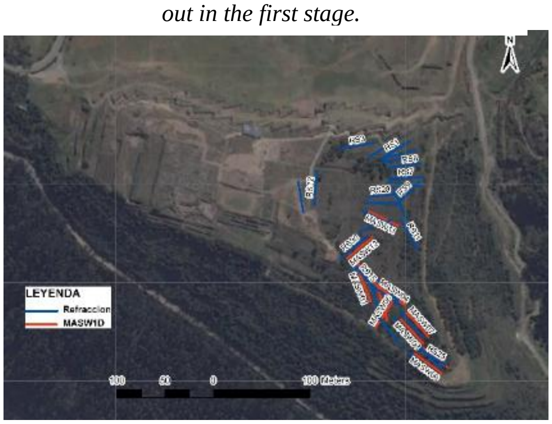

Figure N ° 03: View of Seismic Refraction and MASW of the second stage.

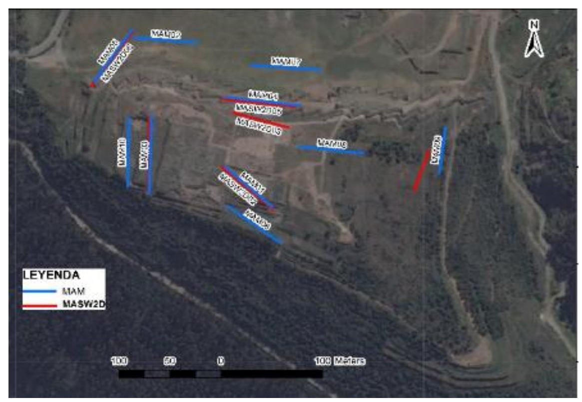

Figure N ° 04: View of MAM and MASW tests of the third stage.

Figure N ° 05: View of GPR tests carried out in the third stage.

Figure N ° 06: Location view of Microtremors realized.

4. Analysis and interpretation of Geophysical Tests

4.1 Seismic Refraction

According to the seismic profiles, the maximum depth of investigation has been 15.0m with a good reliability in the results. Vp velocities ranges from 210 m/s to 2300 m/s. It has been established three types of strata whose compactness varies from dense to very dense, the potencies of these strata are different. In Figures N° 07 to 07 made reference to line LS-30 for the description of the material type.

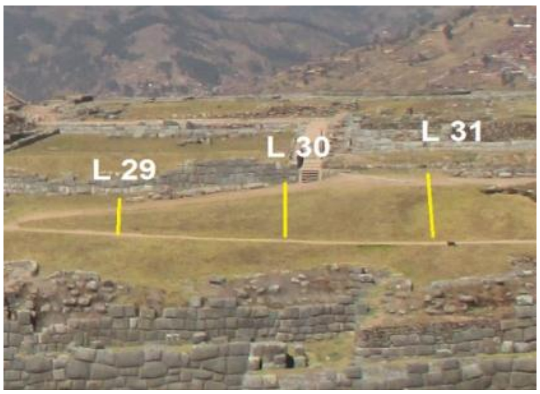

Figure N ° 07: Location of LS-29, LS-30 and LS-31 Seismic Refraction Lines.

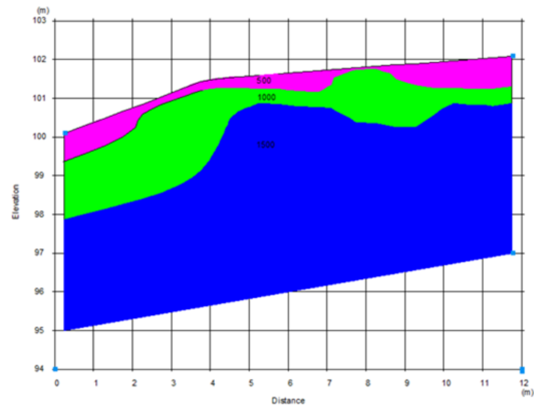

Figure N ° 08: Seismic profile of the LS-30 line.

4.2 MASW

From the results obtained in the one-dimensional shear velocity profile, it was determined that the minimum shear velocity (Vs) is 220 m/s, and the maximum value is 616 m/s, and in the profile corresponding to the MASW 2D test has determined that the minimum shear velocity is 193 m/s, and the maximum value is 597m/s, so the material type has a loose compactness to very dense. Figures No. 09 and No. 10.

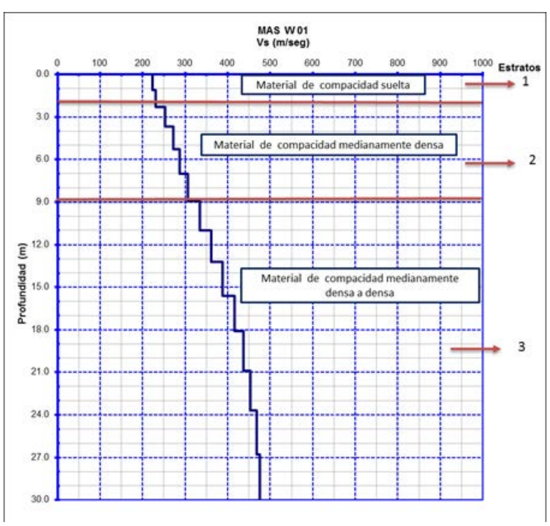

Figure N ° 09: Vs Profile of the LS-30 line.

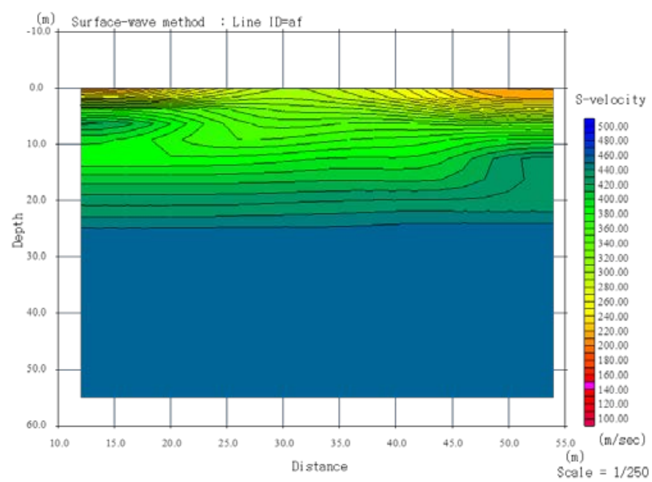

Figure N ° 10: 2D Vs Profile of MASW 02D-02.

4.3 MAM

In a one-dimensional shear wave propagation velocity profile, it was determined that the minimum shear velocity is 180 m/s, and the maximum value is 950 m/s, reached a depth of 105 m. Figure N° 11 shows the dispersion curve generated and Figure N° 12 shows the increase of S wave velocities.

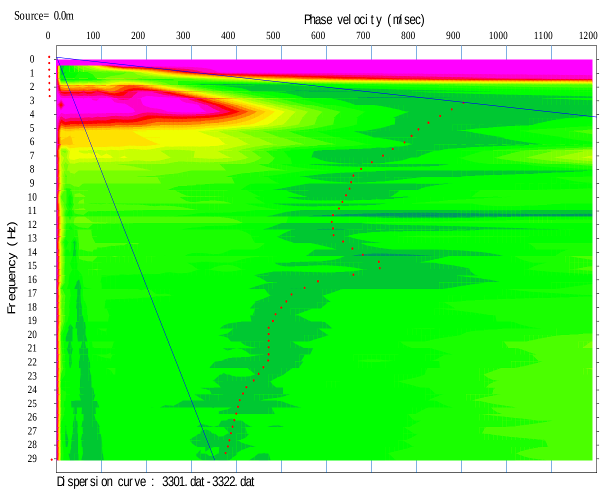

Figure N°11. Dispersion Curve - MAM.

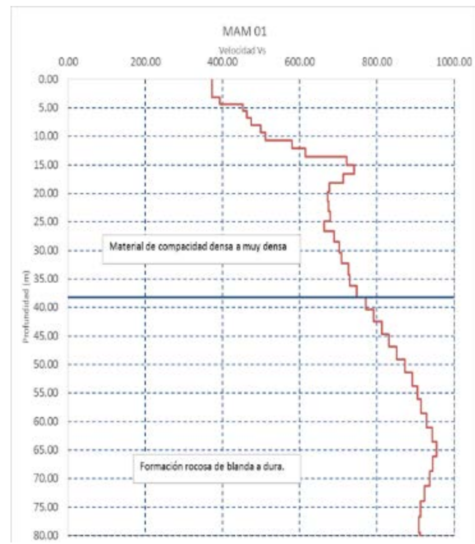

Figure N° 12: Vs Profile obtained with the MAM test.

4.4 Georadar Profile (GPR) - Radargram

According to the results of the radargrams, in general terms, it has been possible to identify three types of materials such as clays with rock fragments, with variable power of 0.5m to 3.0m, clays with gravel and clay with sand with varying powers of 2.0m to 4.0m. In some radargrams the presence of isolated lytic fragments was found, which may be part of the buried Inca walls. Figure 13 shows the location of the lines with GPR in the esplanade and in Figure Nº14 you can see anomalies in the form of a strip that can be part of Inca walls.

Figure N°13: Location of Lines with Georadar (arrow: LS-05).

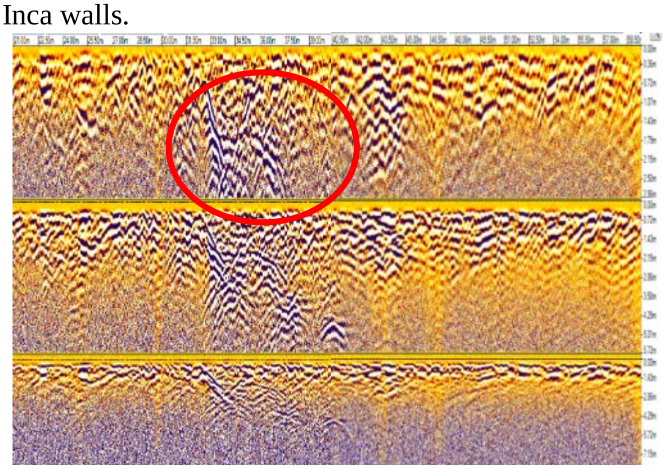

Figure 14: Radargram LG-05 shows anomalies in the shape of a fringe. (first stage).

4.5 Microtremors - H/V

Due to the lack of information regarding vibration periods in the study area, microtremors were measured in 64 points distributed throughout the all area. Through the analysis of the H/V spectra (Nakamura method) the fundamental vibration periods have been determined, which vary from 0.35 to 0.57 sec (Annex 01).

In Figure 15, three zones can be seen, the light green color represents periods of vibration smaller than 0.4 sec; The yellow color represents periods of vibration is within the range of 0.4 to 0.5 sec; covering most of the area Sacsayhuamán and red periods greater or equal than 0.5 sec.

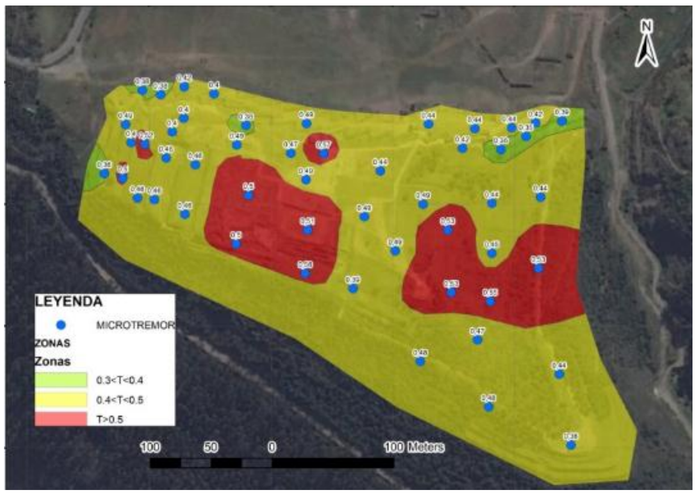

Figure N ° 15: Period Intensity Map.

5.0 Two-dimensional Dynamic Analysis

In order to perform the dynamic analysis, it is necessary to know the stress-strain behavior of the medium (damping and Go/Gmax curves), geometric conditions (topography and stratospheric depth) and seismic conditions (time-history, PGA rock) . Since there were no data on historical earthquakes, the seismic hazard was evaluated and a synthetic accelerogram was generated.

5.1 Seismic Hazard and Synthetic Accelerogram
For the evaluation of the Seismic Hazard, with a probabilistic method, we used the subduction and continental seismic sources and the recurrence parameters established by Gamarra (2009) [2], and the rock spectral acceleration attenuation laws for subduction earthquakes and earthquakes Continental de Young et al. (1997) [3] and Sadigh, et. al. (1997) [4] respectively. As a result the uniform hazard spectrum was obtained for a return period of 475 years and a probability of 10% being exceeded in the exposure period of 50 years.

For the generation of the synthetic accelerogram we used the methodology proposed by Lihanand and Tseng (1988) [5], which consists of taking the time-history of accelerations to fit them into a response spectrum that defines the movement to be reproduced for a dynamic response analysis.

In order to define the synthetic accelerogram, a seismic record was used that has as focal mechanism the seismic event of the continental type, for which, the earthquake with epicenter in

Paruro-Cusco occurred on September 27, 2014, recorded at the Tambomachay seismic station. Figure N°16 shows the uniform hazard spectrum, the matched spectrum of synthetic accelerogram is shown in Figure No. 17, where the maximum acceleration (PGArock) is 0.21g.

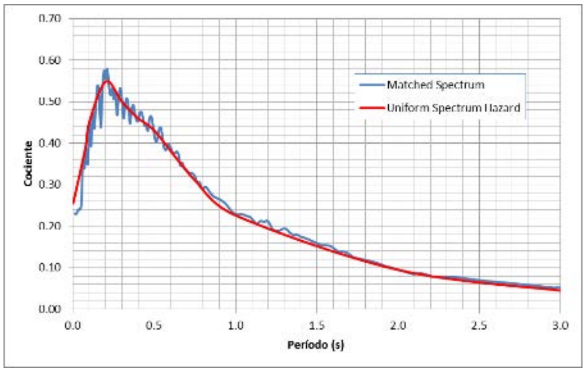

Figure 16: Uniform hazard spectrum and matched spectrum of synthetic accelerogram.

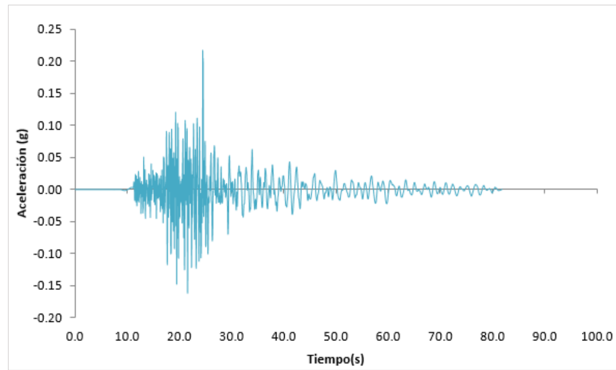

Figure N ° 17: Synthetic Accelerogram.

5.2 Dynamic analysis

The analysis was performed using the two-dimensional Equivalent Linear Method (Seed and Idriss, 1969) [6], using the Shearing Module Reduction factors for soil and rock. In the case of the base rock it is considered a linear behavior, with damping ratio equal to 0.35. Equivalent Linear behavior was considered for the intermediate and superior material. For modeling, he used the Quake/W package of GEO-STUDIO 2007, version 7.19.
Likewise, two geotechnical sections named A-A and B-B were used, as shown in Figure N° 18, with which the response was evaluated at 8 points on the surface of the profile. As a final result it is obtained the time-history record of each point getting the maximum acceleration product of the amplification. Subsequently, the ratio between the Fourier amplitude spectra of the surface register and the amplitude spectrum of the input movement register was calculated to evaluate the period of vibration at large deformations. Figure N° 19 shows the geometric model with the stratigraphy of the geotechnical section AA. The lower stratum corresponds to a soft to hard rock with a Vs up to 760 m/s, the middle stratum is a dense to very dense material with a Vs within the range of 360 m/s to 760 m/s, the surface stratum is a soil of medium to dense compactness with a Vs within the range of 180 m/s to 360 m/s.

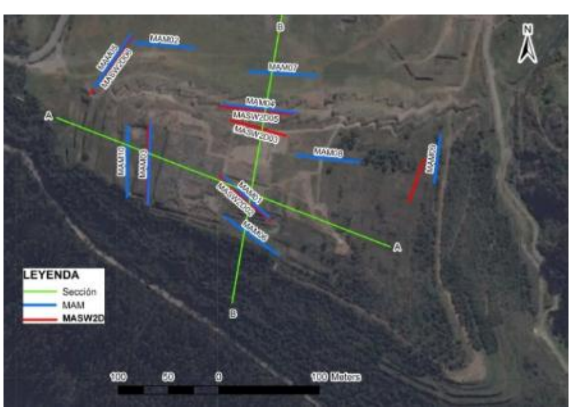

Figure N ° 18: Sections used for two-dimensional model. Source: Prepared by the authors.

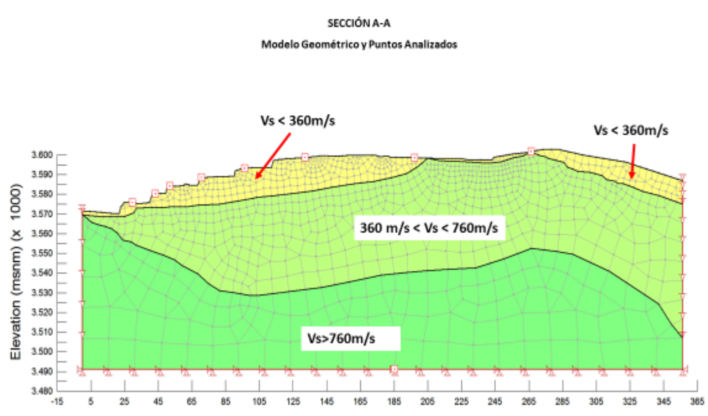

Figure N ° 19: Geometric Model. Source: Prepared by the authors.

Table No. 02 shows the summary of the results in Sections A-A and B-B.

TABLE Nº 02. Accelerations, velocities, displacements, amplification ratio (AR) and period of vibration in sections A-A and B-B.

SECTION A-A						SECTION B-B					
Point	**Ac. (g)**	**V (cm/s)**	**Dis. (cm)**	**AR**	**T (s)**	**Point**	**Ac. (g)**	**V (cm/s)**	**Dis. (cm)**	**AR**	**T (s)**
p-1	0.250	16.1	4.7	1.19	0.42	p-a	0.276	16.2	5.2	1.32	0.38
p-2	0.289	17.6	4.8	1.38	0.42	p-b	0.330	16.8	10.5	1.57	0.38
p-3	0.279	18.7	4.9	1.33	0.42	p-c	0.258	17.8	4.6	1.23	0.39
p-4	0.310	19.9	5.0	1.48	0.43	p-d	0.306	20.3	5.1	1.46	0.38
p-5	0.327	22.2	6.9	1.56	0.43	p-e	0.342	22.3	5.3	1.63	0.38
p-6	0.288	21.9	7.0	1.37	0.42	p-f	0.330	22.6	5.1	1.57	0.38
p-7	0.235	18.7	4.9	1.12	0.42	p-g	0.317	22.8	4.9	1.51	0.39
p-8	0.238	19.7	5.0	1.13	0.42	p-h	0.275	19.5	4.9	1.31	0.39
p-9	0.238	20.6	5.0	1.13	0.42	p-i	0.254	18.1	4.9	1.21	0.39

Note: Ac: Maximum Acceleration, V: Maximum Speed, Dis: Maximum Displacement, AR: Amplification Ratio (Ac / PGArock), T: Fundamental Vibration Period.

5.3 Validation of the Model based on Spectral Ratio

For the validation of the obtained results we used the spectral ratio method of the two-dimensional analysis and the H/V (Nakamura method) [7]. The first consists in dividing the Fourier spectrum of the surface register and the rock record to obtain the characteristic vibration period. The second is to determine the characteristic vibration period by measuring microtremors. From this it is observed that by means of both methodologies the values of periods obtained are similar as shown in Figures N°20 and 21.

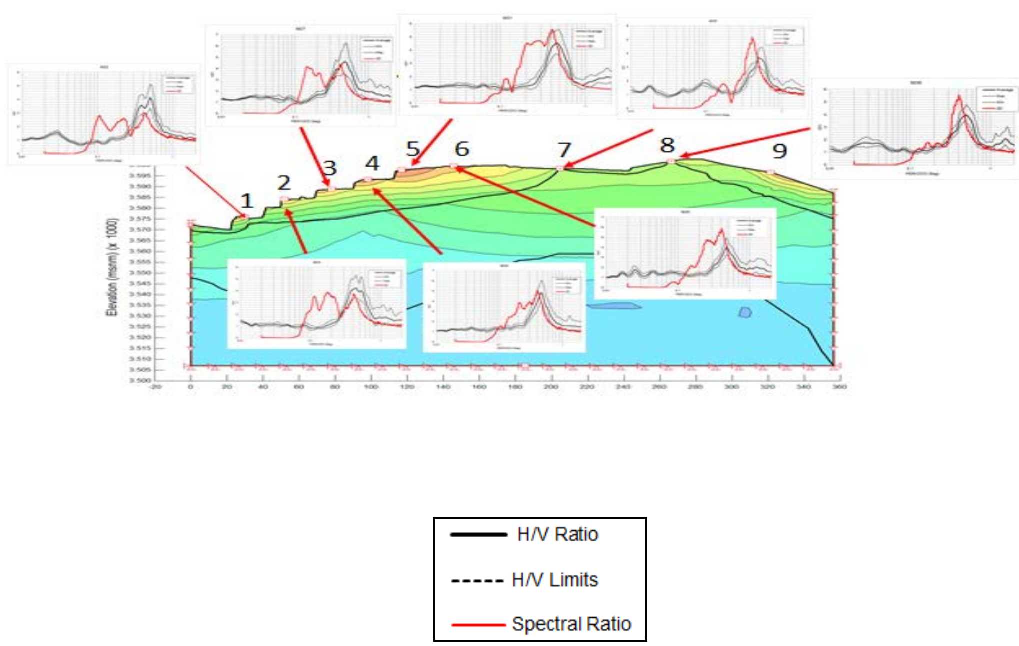

Figure No. 20: Comparison of spectral ratio of Section A-A.

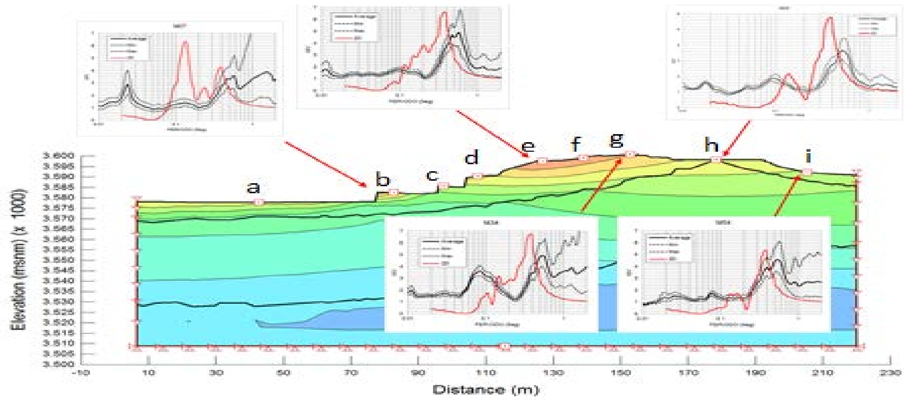

Figure No. 21: Comparison of spectral ratio of Section B-B.

6. Analysis and discussion of results

In section A-A, the highest response in terms of acceleration occurs in the highest part, in points p-4 and p-5 (Figure N°20), the maximum accelerations obtained are 0.310g and 0.327g respectively. It being higher than the acceleration obtained in rock. Considering the topography conditions and the soil type an amplification has been obtained varying from 1.48 to 1.56 respectively. The fundamental period of vibration on these points was also evaluated, being 0.43sec. In general, in this profile the range of surface accelerations ranges from 0.235g to 0.327g, with an amplification of 1.12 to 1.56 and fundamental vibration periods vary from 0.42 to 0.43s. In addition, it is observed that the values of maximum velocity are within the range of 16.1 cm/s to 22.2 cm/s and the maximum displacement of 4.7cm to 7.0cm.

In section B-B, the highest response in terms of acceleration occurs at the top, at points "d", "e", "f" and "g" (Figure N°21). The maximum acceleration at point "e" is 0.342g, while at points "d", "f" and "g" is 0.306g, 0.330g and 0.317g respectively. At these points the accelerations are superior to the acceleration in the rock, considering the conditions of topography and type of soil occurs amplification of 1.46, 1.63, 1.57 and 1.51 respectively. In addition, the fundamental period of vibration was evaluated on these points being 0.38s. In general, in this profile the range of surface accelerations ranges from 0.254g to 0.342g, with an amplification of 1.21 to 1.63 and fundamental vibration periods vary from 0.38 to 0.39s. In addition, it is observed that the maximum velocities values are within the range of 16.2 cm/s to 22.6 cm/s and the maximum displacement of 4.6cm to 10.5cm.

When comparing both sections it is observed that the acceleration values obtained on the surface are similar, therefore also in amplification values, however, there is a slight variation in values of periods of characteristic vibration, due to the different conditions of deformations occurring in the soil. Thus, these periods were also compared with the values of vibration periods obtained in the measurement with microtremors, obtaining similar results. These effects of amplification of motion were expected due to topography conditions and soil type. At the same time the measurement of the period of vibration in the limestone rock formation, *Rodadero* area, was made. It was not possible to define the characteristic period, however, when assessing the amplitude of the H/V ratio of Nakamura we obtained values close to unity, this can be said to be characteristic of a rock formation. On the other hand, when evaluating the periods of environmental vibration very close to the diorite rock formation, *Muyuqarmaka* zone, period values of 0.38s to 0.40s were obtained, a possible explanation of these values is that below the rock formation could exist a zone heavily weathered and therefore the period is similar to a dense soil that is transmitted to the rocky formation at the surface. In general, the vibration period of the studied Sacsayhuamán zone is between 0.37 and 0.57s.

7. Conclusions

- The combination of the different methods of indirect exploration (geophysics) allowed obtain, with the required precision, the elastic parameters of the soil.
- The interaction between MASW and MAM methods allowed to obtain profiles of S waves to depths of 105 m.
- Through the technique of the Georadar three types of materials were identified that are below the Inca terraces in Saqsayhuamán: cultivation soil, gravels with presence of fine material and fragments of rock, as well as anomalies in the form of a vertical strip.
- From the two-dimensional analysis it is observed that the maximum acceleration at the surface is from 0.235g to 0.342g, consequently it is amplified from 1.12 and 1.63. The fundamental period of vibration on average is 0.40s. The vibration period of the Sacsayhuamán terrain obtained by measuring microtremors is comprised of 0.35s and 0.57s. The maximum speed is 16.1cm / s to 22.6cm / s and the maximum displacement is 4.7cm to 10.5cm.
- This information will allow us to analyze the damage caused to the Inca walls, to propose alternative solutions and to simulate the behavior of the existing walls in the presence of a seismic event to prevent future damages and collapses.
- The importance of a two-dimensional dynamic analysis is emphasized in places where the conditions are not assumed in normal amplification analyzes (horizontal strata, infinite on both sides). The geometrical particularity of the slopes will generate important amplifications, which must be quantified appropriately.

8. Acknowledgments

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