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Authors:	Olegario Alonso-Pandavenes, Gabriela Torres, Francisco Javier Torrijo and Julio Garzón-Roca
Status:	Revised version

Response to the reviewers and description of the changes made up in the first revised version of the manuscript

Initial Considerations

First of all, the authors would like to thank the contribution of the reviewers for their thorough examination of the manuscript and valuable comments, which will undoubtedly enhance the manuscript's quality. The authors have tried to attend the comments and suggestions of the Reviewers in this revised version of the manuscript. All the comments made by the reviewers are addressed individually. In each case, the reviewer's comment/question is presented first (in italic), then the authors' reply/answer is given next, and, finally, the action prompted by the reply is described.

In the present version of the manuscript, figures, and tables, the content was modified as recommended from Proof-Reading-Service Ltd whom have made English usage.

Editor in chief

Comment 1 – *"The citations in the text and the reference list do not follow the BOEG style. The authors should take a look at "Instructions for Authors" of BOEG and read the sections of 'Citation' and 'Reference list' under 'References' carefully. By strictly following this, the authors should make the necessary changes"*

Reply/Action – The authors thank the reviewer for their time and help. All citations (references and inside the text) were revised and completed, including the DOI where proceed.

Comment 2 – *"The English usage in the manuscript must be improved. The grammatical errors should be aptly rectified. Before submitting the revised manuscript, the authors may take help from one of the companies which provides an English editing service for scientists (for example, Edanz (www.edanzediting.com)), and include the certificate/invoice/receipt as the proof in the revised version of the manuscript"*

Reply/Action – The authors thank the reviewer for their time and valuable help. The English usage was improved and a certification of revised version of manuscript is enclosed (Proof-Reading-Service Ltd).

Reviewer #1

***General comment** – "This paper is well written and a classical HVSR application for seismic site effect and hazard analysis. On the other hand, there are important references missing which are directly connected with the subject and also pioneers of the related works. Therefore, it is very important for the readers for their better understating of the study with the basic studies on the subject. Authors must not only give the references of the following studies but also mention about the differences and the similarities with these studies and the current work.*

1. Kanli, A.I., 2010, "Integrated Approach for Surface Wave Analysis from Near-Surface to Bedrock", Chapter 29, p. 461-476, Advances in Near-Surface Seismology and Ground-Penetrating Radar, Geophysical Developments Series No. 15, SEG Reference Publications, Society of Exploration Geophysics Reference Publications Program, Tulsa, Oklahoma-USA. Publisher: Society of Exploration Geophysicists, American Geophysical Union and Environmental and Engineering Geophysical Society (Ed. Com.: R.D. Miller, J.D. Bradford and K. Holliger), ISBN 978-0-931830-41-9 (Series); ISBN 978-1-56080-224-2 (Volume).

2.Kanli, A.I., Kang T.S., Pınar, A., Tildy, P., Pronay, Z., 2008, A Systematic Geophysical Approach for Site Response of the Dinar Region, South Western Turkey, Journal of Earthquake Engineering, vol. 12:1, S2, p. 165-174.

3. Kanli, A.I., Tildy, P., Pronay, Z., Pınar, A., Hermann, L., 2006, VS30 Mapping and Soil Classification for Seismic Site Effect Evaluation in Dinar Region, SW Turkey, Geophysical Journal International, Volume 165, 1, p. 223-235"

Reply/Action – The authors thank the reviewer for their time and valuable help. The three works mentioned were included as a reference and indicated that they are a new possibility of further lines of investigation from this work.

Reviewer #4

General comment – *"The paper presents an interesting study related to the basement tectonic structure and sediment thickness of a valley, based on a geophysical approach by HVSR test.*
The paper shows a good work quality both in terms of exposition clarity and presentation of results, and in terms of easy understanding of the proposed figures and tables, so, no substantial revisions are needed.
Some minor editorial modify are needed"

Reply/Action – The authors thank the reviewer for their time and valuable help.

Comment 1 – *"please improve the quality text of the legend in the Fig. 2 (better if the text is in vector mode, instead of raster mode)"*

Reply/Action – The authors thank the reviewer for their time and help. The legend was corrected improving the quality of text and resized it to get better resolution for smaller sizes in Fig. 2

Comment 2 – *"please improve all the text of the Fig.3 and Fig. 9; in particular the elevation is not readable, the same for the bar-scale and for the "San Marcos dam" and "Azuela river" texts"*

Reply/Action – The authors thank the reviewer for their time and help. All text were improved with a resize and better resolution for Figures 3 and 9, including a new bar-scale and elevation numbers. Also orthographic error corrected.

Comment 3 – *"please improve the quality text of the legend in the Fig. 4 (better if the text is in vector mode, instead of raster mode)"*

Reply/Action – The authors thank the reviewer for their time and help. The legend was corrected improving the quality of text and resized it to get better resolution for Fig. 4

Comment 4 – *"Please resize the Fig.6 graphs and the legend per each: four graphs in each row is not good. Please consider maximum 2 graphs per row"*

Reply/Action – The authors thank the reviewer for their time and help. The graphs on Fig. 6 were rescaled and using 2 graphs per row. The axis legend and units are now clearer than initial figure. Also corrected an orthographic error in text of figure

Comment 5 – *"Please improve the fig.7 and 8 axis legend: is with poor resolution"*

Reply/Action – The authors thank the reviewer for their time and help. The size and resolution in both axes were improved for figures 7 and 8

Comment 6 – *"Please insert a figure (best if a photo) of the in-situ carried out HVSR test"*

Reply/Action – The authors thank the reviewer for their time and help. A picture of equipment in area of investigation was included inside the Fig. 5 (field data example) with the purpose of don't make changes in total number of figures.

Comment 7 – *"About the importance of the in-situ test authors may evaluate to cite this work:*

- Ferraro A., Grasso S., Massimino M. R., Maugeri M. (2015) - Influence of geotechnical parameters and numerical modelling on local seismic response analysis.
- Castelli, F., Cavallaro, A., Ferraro, A., Grasso, S., Lentini, V., Massimino, M.R. (2018) - Influence of geotechnical parameters and numerical modelling on local seismic response analysis."

Reply/Action – The authors thank the reviewer for their time and help. Included in bibliography first work (from 2015) and comments inside text about it. Second one *Castelli, F., Cavallaro, A., Ferraro, A., Grasso, S., Lentini, V., Massimino, M.R. (2018) - Influence of geotechnical parameters and numerical modelling on local seismic response analysis."* can't be found

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Yours sincerely,

Mr. Olegario Alonso-Pandavenes (the corresponding author)
(omalonso@uce.edu.ec)

BASEMENT TECTONIC STRUCTURE AND SEDIMENT THICKNESS OF A VALLEY DEFINED USING HVSR GEOPHYSICAL INVESTIGATION. AZUELA VALLEY. ECUADOR

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Abstract

The use of a small set of boreholes, as fixed information of the basement, combined with the analysis of microtremor surveys can provide a transversal detailed section of a valley. In this paper, the horizontal to vertical spectral ratio (HVSR) technique was applied as a quick and economic method to establish the thickness of the sediments existing over the rock basement in the San Marcos dam area, located at the Azuela valley (Cayambe, Ecuador). Previous investigations conducted for the construction of the dam, with a length of 700 m, did not reach the bottom of the valley; only the abutments were properly defined, where the rock being close to the ground surface at those areas. Involving a few boreholes as control points, a relation between the natural frequency of the ground vibration and the sediment thickness was established. 20 HVSR single station points were measured and analyzed in the three main directions (N-S, E-W and Z) of the components of the ground natural

vibration (rumour) and using the natural vibration frequency at each point, a correlation was established with the sediment thickness. From that point, the geological cross-section of the bottom of the valley could be delineated, revealing some tectonic structures (faults) not defined in the previous geotechnical investigations and whose evidence may be useful in further control dam settlement studies. The proposed formulation can also be used as a quick tool to accurately investigate the area around the dam and define other tectonic structures not previously evidenced.

Keywords: HVSR; Microtremor; H/V Spectral ratio; Depth of bedrock; Azuela valley

1. Introduction

Seismic vibrations that result from either anthropic or natural sources are called microtremors. They can vary in energy daily or weekly, or in the position of sources, but they are still constant in frequency over time (Asten 2004; Bonnefoy-Claudet et al. 2004; SESAME 2004). Nakamura (1989) hypothesised that the vertical component of ambient noise has the characteristics of source to sediments surface ground and is relatively influenced by Rayleigh waves on the sediments. Therefore, the vertical component may be used to remove both the source and the Rayleigh wave effects from the horizontal components. This technique is called HVSR (Horizontal to Vertical Spectral Ratio), H/V, or the Nakamura technique, and it can be applied both in earthquake research (determination of fundamental periods of vibration) and in geological logging (classification of geological materials using V_s and V_{s30}) through the analysis of an ellipticity curve (Nakamura 1989; Delgado et al. 2015; Pamuk et al. 2019; Jirasakjamroonsri et al. 2019). The HVSR technique can identify the fundamental resonant frequency of a sedimentary layer and its implied amplification factors. This has been shown by other researchers (Ohmachi et al. 1991; Lermo et al. 1992; Field and Jacob 1995; Kanli 2010) who used the H/V ratio of noise to identify the fundamental resonant frequency of sediments. The application of this technique only requires a high geophysical impedance (relationship between the bulk density of a medium and the velocity of the seismic wave propagating through it) contrast of more than two times between existing media to obtain successful results (Nakamura 1998; Vella et al. 2013; Hellel et al. 2019).

Since 2006, the Autonomous Decentralized Government of the Province of Pichincha (Ecuador), hereafter GADPP, has been building an irrigation system. This system involves the construction of a fine-grained core earth dam to the south of the San Marcos lagoon, in the Azuela River valley, which serves as a reservoir for water distribution (*www.pichincha.org.ec*). The reservoir is expected to start to being filled by the end of 2020, and the commissioner needs to control the responses of the dam's foundation and the ground until reaching the final capacity (13 m above the base level of the lagoon). Knowledge about the geology and the structure of the bottom of the valley and the sediments' thicknesses are both required for this process, but they are undetermined for now: the tests (boreholes) and surveys (seismic refraction) conducted in the geological and geotechnical study (in 2009) did not reach the level of the bedrock, especially in the central zone of the infrastructure where a greater thickness of sediments exist (GADPP 2009).

Thus, this paper shows the application of the HVSR technique to quantify the thickness of the sedimentary materials overlying the basement of the San Marcos dam. The high contrast of impedances that exists among the recent sediments (flow of pyroclasts, volcano sedimentary materials, and alluvial and lacustrine sediments) and the compact basement formed by lavas belonging to the Angochagua formation in the study area enabled the application of the HVSR technique. Both bulk density and seismic velocity have a high difference in values that gives the needed impedance contrast: previous studies (GADPP 2009) have shown that the velocity of the primary waves (V_p) was around 2000 m/s in the highly compacted sediments and over 4000 m/s in the basement rock (lavas); this results in a ratio of 2 between them (also in impedance).

The identification of the position of the basement (bedrock) of the San Marcos dam was obtained from the results of a Rayleigh wave analysis and the ratio of the H/V components, by using a mathematical formulation that relates the fundamental frequency of vibration of the ground and the thickness of the sediments (Chang et al. 2015). This completely determined the east-west cross-section of the basement, and the structure of the Azuela River was clearly defined. The established relation may provide a quick and economical tool for prospecting bigger areas around the dam to delineate a completely three-dimensional picture of the whole valley. It could be used to accurately define the tectonic and structure of the basement around even the deepest areas.

2. Geographical setting and geological framework

The valley of Azuela River is located in the municipality of Cayambe, in the eastern part of the province of Pichincha, in the north of Ecuador (**Fig. 1**). It was originally a valley embedded in a deep V shape enhanced by the existence of north-south and northwest-southeast direction faults, which have been covered by sediments from the Holocene to actual times (Torres 2018). The studied area is geomorphologically characterised by the presence of a lagoon, San Marcos, which was formed after a past eruption of the Cayambe volcano. This natural water reservoir is located to the north, about 10 kilometres north of the crater (**Fig. 2**), in which a pyroclastic flow blocked the valley and generated water and sediment retention (Samaniego et al. 1998).

The geology of the area is characterised by the presence of a Pleistocene basement formed by lavas and compact volcanic products (cemented pyroclasts) belonging to the Angochagua formation. A sequence of volcanic materials (flows, pyroclastic, and ash) and glacial, alluvial, and lacustrine sediments have been deposited over them (Torres 2018).

The geological cartography (**Fig. 2**) was performed by GADPP (2009) and subsequently reviewed by Torres (2018). It shows how the pyroclastic flowed from the Cayambe volcano (to the southwest, outside the image) blocked the valley of the Azuela River. These materials have been dated to 4000 B.P., and came from a San Marcos type eruption, one of the strongest scenarios that could produce this volcano. These pyroclastic sediments functioned as a natural dam that allowed the formation of the San Marcos lagoon and the sedimentary series on which the constructed dam is currently located (Samaniego et al. 2004).

The geomorphology of the valley area presents an accentuated V shape which has been gently softened by glaciers (the Ismuquiru river valley, just to the west of the Azuela valley, has a clear U-shape typical of glacial events) with slopes at its flanks of 16º in the west and 20º in the east. The eastern flank, over the dam crest, has flatter slopes and a plain area raised 100 m over the lagoon water level. This could be due to the effects of glacial erosion. The slopes to the west keep the original acute form of the valley, probably because they were formed by the action of the north-south direction fault that would run through the centre of the current lagoon (Torres 2018). The actual level of the land in this area is at an average of 3420 m above sea level.

The structural features of the area, like faults and folds, are not clearly defined. Most of them are covered by the sediments, overburden, and alteration soils that hide the rock and faults. These features are briefly delineated in **Fig. 2**. Faults that are drawn to the west of the lagoon, with an almost east-west direction, could be observed in the field. The faults that cross from north to south and northwest to southeast at the centre of the Azuela valley are supported by geological sections of the dam made for its construction (Torres 2018).

The direction of these faults is consistent with the strain processes from the subduction zone at the west coast of Ecuador. The Nazca plate is subducting South American plate and this is the first origin of this dextral faulting, parallel to the coast, which is also the focus of seismicity and earthquakes. Thus, the San Marcos dam area is located in a high seismic hazard zone as indicated by the Ecuadorian Seismic Classification (Egüez and Aspden 1993). The value of PGA calculated for rocks in this zone is between 300 and 310 gal (1 gal equal to 0,01 m/s^2), but it could reach between 400 and 500 gal if local effects (amplification factors due to thick sedimentary cover) are considered (Torres 2018).

3. Construction project and previous surveys

The geological and geotechnical study for the construction of the San Marcos dam included boreholes and geophysical researches conducted at the dam axis. The aim was to complement the data obtained previously by GADPP (2009). **Fig. 3** shows the construction cross section of the dam along with the five boreholes conducted. Perforations at or near the ends of the profile (P-7A, P-10A, PSM-3, and P-9) cut the basement, while the one executed in the central zone (P8) did not reach it.

The geological profile showed that the basement of the valley at its central part is deeper than 75 m (reached depth in P8 borehole), with the presence of several vertical faults accentuating this deepening towards the centre and east (right edge, where the Azuela River is located). Measured seismic velocities (V_p) enable the interface between the recent sedimentary materials ($V_p \approx 1725$ m/s) and the pyroclastic flows ($V_p \approx 2210$ m/s) to be located at depths of 34 m from the current topographic surface. Thus, the stratigraphic sequence in the construction zone of the dam has more than 35 m (in the central zone it exceeds 40 m) of alluvial and/or lacustrine sediments (distal or low intensity of flow) which lay over volcanic sedimentary material of pyroclastic flow type. Auxiliary 22-m-depth SPT surveys done before constructing the dam foundation, demonstrated an increase of compaction values of the ground (GADPP 2009).

4. Experimental study

An experimental study was performed at the toe of the San Marcos dam, on the downwards side of the water flow and over it, using the single station HVSR technique. Since the area was saturated, the station points could not be placed continuous and equal spaced as desired. A total of 17 single station points were investigated close to the dam toe and spaced over, selecting harder and unsaturated soils (unequal distributed in distance). Additionally, three station points were located over the crest of the dam. **Fig. 3** and **Fig. 4** show the location of the station points in section and plan view, respectively. Some points were not along investigated cross-section (marked as purple line in **Fig. 4**). Points 18, 19, and 20 were measured on the top of the dam and points 1, 4, 7, 10, 12, 17, and 14 were also extrapolated to the interpreted section. Some station points were taken at the same location where boreholes were performed or close to them (the exact coordinates of the position of old boreholes were not available) to allow the interpretation of the results. The frequency and period of each 20 points measured are listed in **Table 1**.

The HVSR technique is based on the spectral analysis of the rumour collected on the surface of the ground. The application of microtremor devices can be made through an array or alignment of geophones, such as the ReMi technique or, as in this case, with the implantation of a single station triaxial set of geophones that collect vibrations in three spatial directions (N-S, E-W, and vertically). At each station point, the measuring device was implanted on the ground, as firmly as possible and protected from the wind or external movements, with an orientation to the magnetic north of one of the horizontal components, established with the support of a compass. The device was connected to a computer to control the equipment and record the data. Since measurements of records need sufficient time to obtain enough data information for further analysis, registration times of more than 20 minutes were performed, following the guidelines indicated for this type of measurements (SESAME 2004). An example of this measured data is shown in **Fig. 5-A,** and so the used equipment **(Fig. 5-C)**.

Raw data processing was carried out using the software GEOPSY v.2019 (SESAME 2004), and consisted of the generation of a windowing from 20 to 25 seconds without overlapping (**Fig. 5-B**). To obtain the final windows to be analysed, anti-triggering filters were applied to the raw signal and, in certain cases, also to the filtered signal (low pass filter with a value of 5 Hz), cleaning the record data from transients. Transients were defined as a comparison between the average signal amplitude over a short time period of one second t_{STA}, STA, and the average signal amplitude over a longer time period of 30 seconds t_{LTA}, LTA. Windows that meet with STA/LTA ratios between 0.05 and 0.5 may be considered as stationary noise. In these spaces of the filtering window, the Fast Fourier Transform (FFT) was applied to each delimited space or window (Bard 2004).

The curves of the horizontal components were combined squared average to obtain the relationship against the vertical one (H/V), previously applying a Kono and Ohmachi (1998) smoothing filter type of 30-40%, with cosine or triangular type windows to every component (H and V). The final HVSR was obtained by averaging the H/V amplitudes from all selected windows (see selected examples of this in **Fig 6**), drawing in colours calculations for every window. The average of them, as a black continuous curve, and the standard deviations values for each frequency were estimated from the H/V amplitude logarithm (dotted black lines in **Fig. 6**). The use of calculation parameters was selected following the recommendations of the SESAME Project (Bard 2004; SESAME 2004).

5. Interpretation of the field data

Interpretation of the field data was done using the GEOPSY software. The relationship between the dominant peak frequency (frequency of the fundamental mode of ground vibration) and the thickness of sediments over the basement was quantitatively established. Nakamura (1989) and Albarello et al. (2011) proposed the basis of this process considering that the Rayleigh waves, in fundamental mode, dominate the environmental vibrations and these propagate in the sediments and soils that overlie a basement in a homogeneous way.

Previous studies have shown that a large-amplitude HVSR peak can be associated to a high impedance contrast between the sedimentary cover and the basement, while a low amplitude peak relates to a lower contrast, indicating the presence of stiff soils (Bonnefoy-Claudet et al. 2006). In 1989, Nakamura suggested that the origin of the fundamental frequencies is related to the resonance of the shear wave in a single layer of sediment and, therefore, the thickness of the layer (*H*) can be related to the fundamental frequency (peak) of the H/V spectral relationship, f_o, according to the relationship:

$$f_o = \frac{n\,V_s}{4\,H} \quad (1)$$

Where *n* are the modes of vibration without attenuation or irregularities and V_s is the velocity of the shear wave in the sediments. However, the definition of this shear wave velocity in the first few metres is difficult to obtain. Budny (1984), based on correlations with geotechnical surveys, indicated that velocity V_s might be described as a function of depth (*z*) as:

$$V_s(z) \approx V_0\,(1+z)^x \quad (2)$$

Where V_o is the average shear wave velocity and *x* is a constant (empirically obtained). Based on Budny's investigations, and using data from well logs (down-hole), Ibs von Seth and Wohlenberg

(1999) determined a good correlation for the peak frequencies of the H/V ratios over a wide range of thicknesses (from tens to thousands of metres), following the expression:

$$Z = a\, f_0{}^{b} \tag{3}$$

Where *Z* is the thickness of sediments over the basement and *a* and *b* are parameters related to the ground. The obtained values of those two parameters over Tertiary and Quaternary sediments in Aachen (western part of the Lower Rhin riverbank) are referred to in **Table 2**. Subsequently, Parolai et al. (2002), Hinzen et al. (2004), Birgören et al. (2009), and Khan and Khan (2016) made adjustments in Eq. (3) according to different places tested, also obtaining different values for *a* and *b* (**Table 2**). This means that in each ground (sedimentary basin) these parameters must be obtained according to the conditions of the materials and their stratigraphic sequence. However, the values of Ibs von Seth and Wohlenberg (1999) and Parolai et al. (2002) are generally used as a reference in some publications (i.e., Khan and Khan 2016).

Table 3 shows the four boreholes available at the axis of the investigated dam where bedrock was reached, and the corresponding results obtained at that location using the HVSR technique. From these results, parameters *a* and *b* were obtained by adjusting Eq. (3) as seen in **Fig. 7**, yielding the following expression:

$$Z = 58.746\, f_0^{-0.247} \tag{4}$$

Adjustment achieved a good match, with a coefficient of determination R^2 of 0.98 (**Fig. 7**), although the contrast points used in the definition of the adjusted curve were relatively few when compared with those presented by other authors (four points here versus more than 30 in the study by Ibs von Seth and Wohlenberg (1999), for example).

6. Analysis and discussion

The fundamental frequency of ground vibrations was found to be in the range of 0.12 Hz and 61.26 Hz (see **Table 1**). These limits are quite broad and generate a range of dispersion which is sufficiently varied to obtain good results in the analysis of the sedimentary basin because it has important variations in depth throughout the investigated section.

The curves obtained have clear peaks in the positions 1, 5, 6, 9, and 10, without the appearance of other dominant modes or peaks, being in the other position's broad peaks, but clearly denote the fundamental frequency in each case. At point 12 (area away from the dam) the test showed a complex curve with several peaks at high frequencies, which would indicate high impedance contrasts in shallow surfaces. Regarding the viability of the H/V curves obtained in the test points 1, 4, and 7, located relatively close to one another, they do not have an amplification value (A_o) in the H/V ratio greater than two. So, this value exceeded those of the rest of the tests carried out (validation conditions according to SESAME 2004). However, these three points were considered in the interpretation.

A comparison using the Eq. (3) for the different values of *a* and *b* given in **Table 2** was conducted. It is interesting to note that coefficients were quite different from those obtained in studies made by Parolai et al. (2002), Hinzen et al. (2004), Birgören et al. (2009), and Khan and Khan (2016). The values obtained for the thickness of the sediments is presented in **Table 4**. Results can also be seen graphically in **Fig. 8** (bi-logarithmic representation) where it may be observed that most of the fitting lines are more tilted than the one reached in this study. This inclination is controlled by the exponent of the formula, which in this case is between four and six times lower than the other proposed ones. The observed numerical differences may be assigned to the nature of the materials: in all investigations related to **Table 2**, the materials were composed of quartz grains and had a homogeneous vertical distribution; in the present work, sediments came from an alteration of andesite rocks with pyroclastic flows overlying the basement, i.e., which were all quartz poor. However, further investigations are needed to confirm these differences.

Fig. 9 shows the San Marcos dam profile with the position of the bedrock drawn from the interpretation of the data given by the old boreholes along with the bedrock prediction interface obtained by applying Eq. (4) on the points surveyed in this study. The observations reveal that the bedrock interface of both interpretations is very similar for points 2, 6, 17, and 19, surveyed points located used for calibrating Eq. (4) with a 4.1% of error between real depth (boreholes), and measured ones (HVSR points). For the rest of the points, the results are consistent with the original drawing of the basin, obtained by drilling and establishing a depth of 99.2 metres in its deepest part (supposedly obtained by point 9). It should be mentioned that the values of points 1, 4, 7, 10, 14, and 17 were extrapolated to the cross-section, as well as those of point 12, 175 m away from it. Nevertheless, the value obtained for this one is consistent with the V-shape of the investigated valley and the closest-lying ones. Although having obtained good results using Eq. (4), further research between various points would be necessary to clearly define the interface of the basement in whole section.

Table 4 and **Fig. 9** show the depth of the basement predicted based on the peak frequency (f_o), obtained on each surveyed point using the new formulation and the ones proposed other authors. The irrationality of the results is clear for the relationships of Ibs von Seth and Wohlenberg (1999), Parolai et al. (2002), and Hinzen et al. (2004), where values of sediment thicknesses of more than 1000 and 2000 m, and less than 1 m appeared. Moreover, comparing the parameters *a* and *b* of the new equation with those obtained by other authors (see **Table 2**), only those obtained by Khan and Khan (2016), were close to the values established in this study. However, the results of thicknesses calculated with these factors greatly differ from those obtained in the adjustment made in this investigation, having only the values between 0.9 and 3.4 Hz as opposed to those that had closer values (the intersection is represented in **Fig. 8**). As the values of f_o move away from this dimension, the results differ exponentially.

Structural information of bedrock can be extracted from **Fig. 9**. The fault name number two, at the left margin of the valley (east), has been recognised in previous studies and marked at the same place as has been identified in this investigation (see **Fig. 3** and **Fig. 9**). Both have a vertical scarp, dipping gently toward the western side, but the difference between the two interpretations is the displacement, which is currently more than ten metres against the five metres in old documents. The old displacement was defined from data at borehole P-9 and helped infer this feature. In this study, data measured around this place can delineate better this displacement and evaluate it more precisely.

On the other hand, two new fault structures have been recognised in the centre of the valley, which are responsible for the depth of it: faults 3 and 4. The former is located towards the eastern side of valley (at the first third). The latter is close to the centre of it (300 m from the eastern side of valley) just where an inferred fault was drawn on construction section (see **Fig. 3** and **Fig. 9**). The drawing of the bottom in all areas of the section had an inversed sawtooth appearance, so it was impossible to define clearly a tectonic feature as faults at the western side (it could be that one was defined between 14 and 15 HVSR points, but not clearly). Across the publications of Alvarado (2012), the sismogenic zone defined at this area is in general a strike-slip type of failure, but the oldest faults have an inversed movement caused by the tension from the subduction zone. In addition, the repetition of outcrops on both sides of the lagoon of lavas from the Angochagua formation leads to thinking about a system of reverse faults that double the size on surface of these materials. No more detailed information can be obtained about the area; the faults 3 and 4 appear shown in the cross section of **Fig 9**, laying towards the western side at 65 and 70 degrees, as an interpretation (same as defined Fault 2 in previous studies), and give the main idea that the main tectonic structure was closed to left margin of the Azuela valley where the basement reached more than a 99 m depth.

No fault or special feature could be defined clearly on the western side of Azuela valley: only mention that the inclination observed at the bottom of the valley, in cross-section, was similar to that of the flanks of the valley in every margin. Thus, the eastern margin over the dam slopes inclined at 19.5º and under it, 20.0º on the other hand, the western flank, on the other side of the main fault, sloped at 15.4º, as did the slope of its margin.

7. Conclusions

The application of passive seismic techniques such as the Nakamura or the H/V spectral ratio (HVSR) allows large areas to be recognised without the need to distribute a longitudinal device with cables, allowing the implementation of devices which are less expensive and more economical research which are also faster than other ones, like boreholes. In this paper, the HVSR technique was used to predict the position of the basement (bedrock) of the San Marcos dam (Ecuador) and define the cross section of the Azuela River valley identifying the sediment thickness too.

A total of 20 points were surveyed using the HVSR technique and the relationship between the frequency of natural vibration of the ground (f_o) and the thickness of the sediments (considering a single layer of unconsolidated materials) was established. Following the equation type proposed by Budny (1984) and developed by other authors, a power law relationship with two parameters of values 58.746 (scaling factor term) and -0.247 (power term) was set. When compared with data obtained from performed boreholes, the new relationship proved to be capable of defining the bedrock interface at San Marcos dam, achieving a coefficient of determination R^2 of 0.98 for those surveyed points closer to the location of the boreholes. For the rest of the points, the results were consistent with the original geological interpretation of the basin, which established a supposed depth of 95.5 to 110 metres in its deepest part.

The results obtained using the new relationship have also been compared with power relationships available in the literature and which have been obtained by other authors for different materials and their stratigraphic sequence. As expected, the predicted values yielded irrationality results in nearly all cases, obtaining values of sediment thicknesses of more than 1000 and 2000 m, and less than 1 m in shallow areas. In other cases (e.g., studies by Khan and Khan 2016), results were close to those obtained with the new relationship, but only for a narrow value of f_o (i.e., between 0.9 and 3.4 Hz).

Having a relationship between f_o and the depth where the bedrock is expected to be found opens new opportunities to enhance the knowledge of the Azuela River valley. First, an accurately cross section of the Azuela valley basement could be drawn along the dam toe in order to locate and define its structural features, like faults, that increased its depth. Once all the surveyed points where computed and the bedrock was drawn, it could be concluded too that the inclination of the slopes of the rocky substratum, at both sides of main fault, was shown to maintain the angle of the upper zone (margin over the dam) with 15.4º in the western margin and in the eastern one; the slope was steeper at the east side, in keeping with the geomorphology of the area. This corroborates the position of the fault generated in the centre of the Azuela River valley.

Thus, through the application of the methodology developed in this study, geological and geotechnical investigations of the position of the bedrock could be made with the application of microtremors measurements in areas with direct information (boreholes as control points) as a quick tool of exploration, even without a lot of boreholes. The formulations obtained could then be used in all measurements of microtremor that occurred within them to obtaining coating thicknesses with an accuracy of less than 4.5% (difference between depth to bedrock in boreholes and HVSR measured points). This can be later extended to larger spaces with the consequent economic savings and can be used in further and deeper investigations about geotechnical parameters and site response, out of the scope of this work but as a new line of investigation (Ferraro et al. 2015; Kanli et al. 2006; Kanli et al. 2008). Also, if the density of points suffice, tectonic structures can be defined too, like in this case.

Author Contributions

Conceptualization, O.Alonso and G. Torres; Data curation O.Alonso and G. Torres; Formal analysis, O. Alonso; Funding acquisition, O. Alonso; Investigation, O.Alonso and G. Torres; Methodology, O.Alonso; Project administration, O.Alonso; Resources, O. Alonso and F.J. Torrijo; Software, O.Alonso and G. Torres; Supervision, F.J. Torrijo; Validation, F.J. Torrijo and J. Garzón- Roca; Visualization, F.J. Torrijo; and J. Garzón- Roca Roles/Writing – original draft, O. Alonso and G. Torres; Writing – review & editing, O. Alonso, F.J. Torrijo and J. Garzón- Roca.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Albarello D, Cakir R, Walsh TJ (2011) Single station ambient vibration measurements in the Puget lowland and coastal area, Washington. DNR-DGER internal report.

Alvarado A (2012) Néotectonique et cinématique de la déformation continentale en Equateur. Thése pour obtener le grade de Docteur de L'Université de Grenoble, Spécialité: Sciences de la Terre, I'Univers, et I'Environnement. France.

Asten MW (2004) Comment on "Microtremor observations of deep sediment resonance in metropolitan Memphis, Tennessee" by Paul Bodin, Kevin Smith, Steve Horton and Howard Hwang. Engineering Geology https://doi.org/10.1016/j.enggeo.2003.09.001

Bard PY and SESAME participants (2004) The SESAME Project: An overview and main results. 13th World Conference on Earthquake Engineering. Paper No. 2207. Vancouver, Canada

Birgören G, Özel O, Syahi B (2009) Bedrock Depth Mapping of the Coast South of İstanbul: Comparison of Analytical and Experimental Analyses. Turkish Journal of Earth Sciences http://doi.org/10.3906 / place-0712-3

Bonnefoy-Claudet S, Cornou C, Bard PY, Cotton F, Moczo P, Kristek J, Fäh D 2006 H/V ratio: a tool for site effects evaluation. Results from 1-D noise simulations. Geophysical Journal Int. http://doi.org/10.1111/j.1365-246X.2006.03154.x

Budny M (1984) SeismischeBestimmung der BodendynamischenKennwerte von oberflächennahenSchichten in Erdbebengebieten der niederheinischenBucht und ihreingenieurseismologischeAnwendung. PhD Thesis, Geol. Inst. University of Cologne Spec. Publ. 57, 208 pp

Chang Y-W, Van Bang P, Loh Ch-H (2015) Identification of Basin Topography Characteristic Using Multivariate Singular Spectrum Analysis: Case Study of the Taipei Basin. Engineering Geology https://doi.org/10.1016/j.enggeo.2015.08.027

Delgado J, Garrido J, Lenti L, Lopez-Casado C, Martino S, Sierra FJ (2015) Unconventional pseudostatic stability analysis of the Diezma landslide (Granada, Spain) based on a high-resolution engineering-geological model. Engineering Geology http://dx.doi.org/10.1016/j.enggeo.2014.11.002

Egüez A, Aspden J (1993) The Meso-Cenozoic evolution of the Ecuadorian Andes. Memory of Second International Symposium Andean Geodynamics. Ext. Abstract 78-181 Oxford, UK

Ferraro A, Grasso S, Massimino MR, Maugeri M (2015) Influence of geotechnical parameters and numerical modelling on local seismic response analysis. Proceedings of the XVI ECSMGE, Geotechnical Engineering for Infrastructure and Development http://doi.org/10.1680/ecsmge.60678

Field EH, Jacob KH (1995) A comparison and test of various site response estimation techniques, including three that are not reference site dependent. Bulletin of the Seismological Society of America 85(4):1127-1143

G.A.D. de la Provincia de Pichincha (GADPP) (2009). Estudios de geología y geotecnia dentro del Proyecto de Riego Cayambe Tabacundo y agua potable Pesillo-Imbabura, cantón Cayambe, provincia de Pichincha. Informe Definitivo. Quito

García-Jerez A, Luzón F, Navarro M, Pérez-Ruíz JA (2006) Characterization of the sedimentary cover of the Zafarraya basin (Southern Spain) by means of ambient noise. Bulletin of the Seismological Society of America http://doi.org/10.1785/0120050061

Hellel M, Oubaiche EH, Chatelain J et al. (2019) Efficiency of ambient vibration HVSR investigations in soil engineering studies: backfill study in the Algiers (Algeria) harbor container terminal. Bull. Eng. Geol. Environ https://doi.org/10.1007/s10064-018-01458-y

Hinzen KG, Scherbaum F, Weber B (2004) On the resolution of H/V measurements to determine sediment thickness, a case study across a normal fault in the Lower Rhine Embayment, Germany. Journal of Earthquake Engineering http://doi.org/10.1080/13632460409350514

Ibs Von Seht M, Wohlenberg J (1999) Microtremor measurements used to map thickness of soft sediments. Bulletin of Seismological Society of America https://doi.org/10.1785/BSSA0890010250

Jirasakjamroonsri A, Poovarodom N, Warnitchai P (2019) Seismic site characteristics of shallow sediments in the Bangkok Metropolitan Region, and their inherent relations. Bull. Eng. Geol. Environ. https://doi.org/10.1007/s10064-017-1220-3

Kanli AI (2010) Integrated approach for surface wave analysis from near-surface to bedrock. In: Miller RD, Bradford JD, Holliger K (eds) Advances in Near-Surface Seismology and Ground-Penetrating Radar, Geophysical Developments Series No. 15:461-476. SEG Reference Publications, Tulsa, Oklahoma (USA).

Kanli AI, Kang T-S, Pınar A, Tildy P, Prónay Z (2008) A Systematic geophysical approach for site response of the Dinar Region, South Western Turkey. Journal of Earthquake Engineering https://doi.org/10.1080/13632460802013966

Kanli AI, Tildy P, Prónay Z, Pınar A, Hermann L (2006) V_{S30} Mapping and soil classification for seismic site effect evaluation in Dinar Region, SW Turkey. Geophysical Journal International https://doi.org/10.1111/j.1365-246X.2006.02882.x

Khan S, Khan MA (2016) Mapping sediment thickness of Islamabad city using empirical relationships: Implications for seismic hazard assessment. J Earth Syst Sci https://doi.org/10.1007/s12040-016-0675-0

Konno K, Ohmachi T (1998) Ground-Motion Characteristics Estimated from Spectral Ratio between Horizontal and Vertical Components of Microtremor. Bulletin of Seismological Society of America 88(1):228-241.

Lermo JF, Lermo S, Chavez-Garcia J (1992) Site Effect Evaluation using microtremors: a review (abstract). *EOS* 73, 352.

Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremors on the ground surface. Quarterly Report of Railway Technical Research Institute (RTRI) 30:25-33

Ohmachi T, Nakamura Y, Toshinawa T (1991) Ground Motion Characteristics in the San Francisco Bay Area detected by Microtremor Measurements. International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 11-15 March, 1643-1648 St. Louis, Missouri Paper LP08

Pamuk E, Özdağ ÖC, Akgün M (2019) Soil characterization of Bornova Plain (Izmir, Turkey) and its surroundings using a combined survey of MASW and ReMi methods and Nakamura's (HVSR) technique. Bull. Eng. Geol. Environ. https://doi.org/10.1007/s10064-018-1293-7

Parolai S, Bormann P, Milkereit C (2002) New relationships between Vs, thickness of sediments, and resonance frequency calculated by the H/V ratio of seismic noise for Cologne Area (Germany). Bulletin of Seismological Society of America https://doi.org/10.1785/0120010248

Samaniego P, Monzier M, Robin C, Hall ML (1998) Late Holocene eruptive activity at Nevado Cayambe Volcano, Ecuador. Bulletin of Volcanology 59:451-459

Samaniego P, Eissen J-P, Monzier M, Robin C, Alvarado A, Yepes H (2004) Los peligros volcánicos asociados con el Cayambe. Instituto Geofísico, Quito

SESAME (2004) Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: SESAME, European project, WP12. Deliverable D23.12.

Torres GF (2018) La amenaza sísmica y volcánica de la presa de la laguna San Marcos. Cayambe-Pichincha. Trabajo de Titulación (BsC Thesis). Universidad Central de Ecuador. Quito *http://www.dspace.uce.edu.ec/handle/25000/16316*. Accessed 19 may 2019

Vella A, Galea P, D'Amico S (2013) Site frequency response characterization of the Maltese islands based on ambient noise H/V ratios. Engineering Geology https://doi.org/10.1016/j.enggeo.2013.06.006

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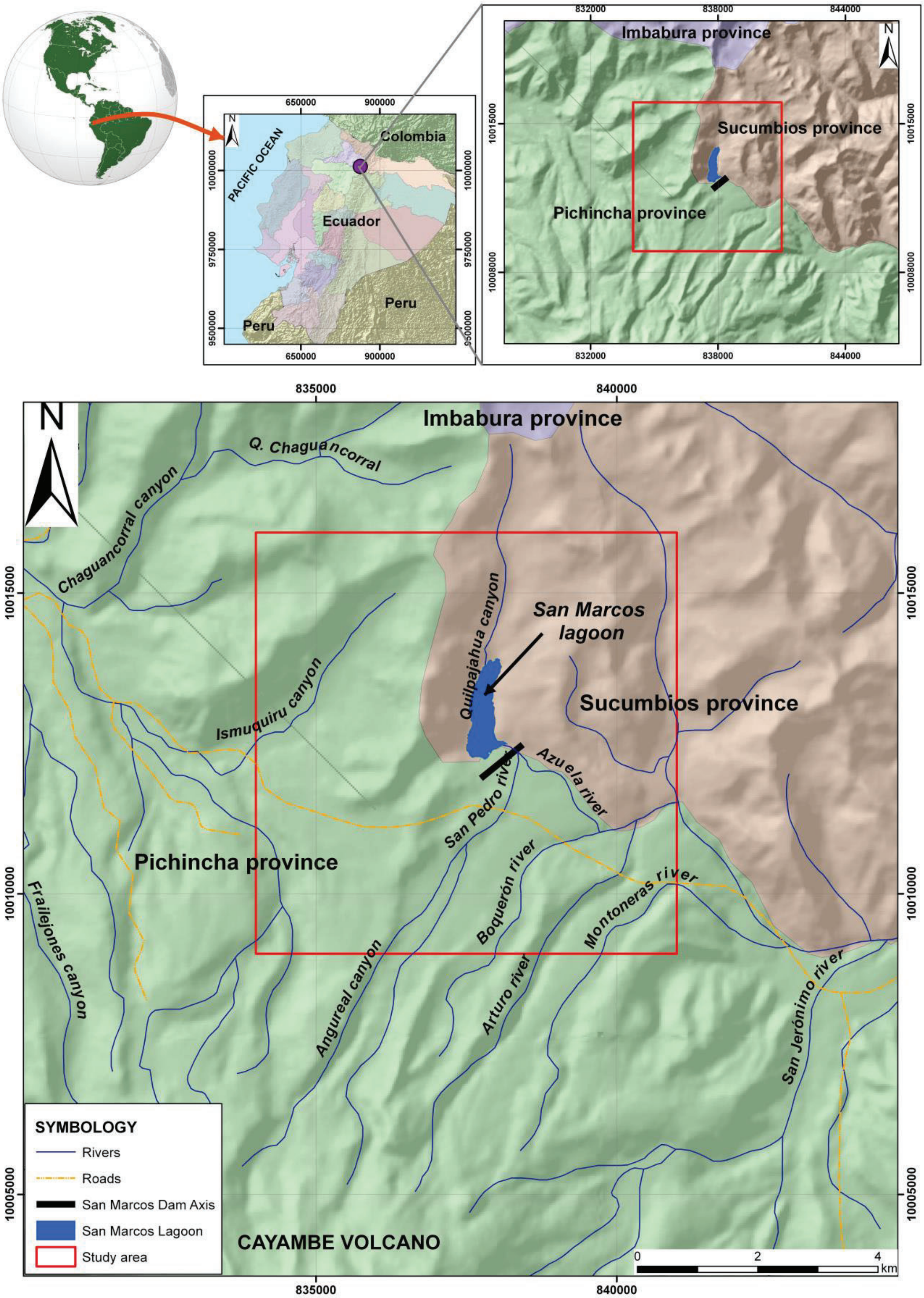

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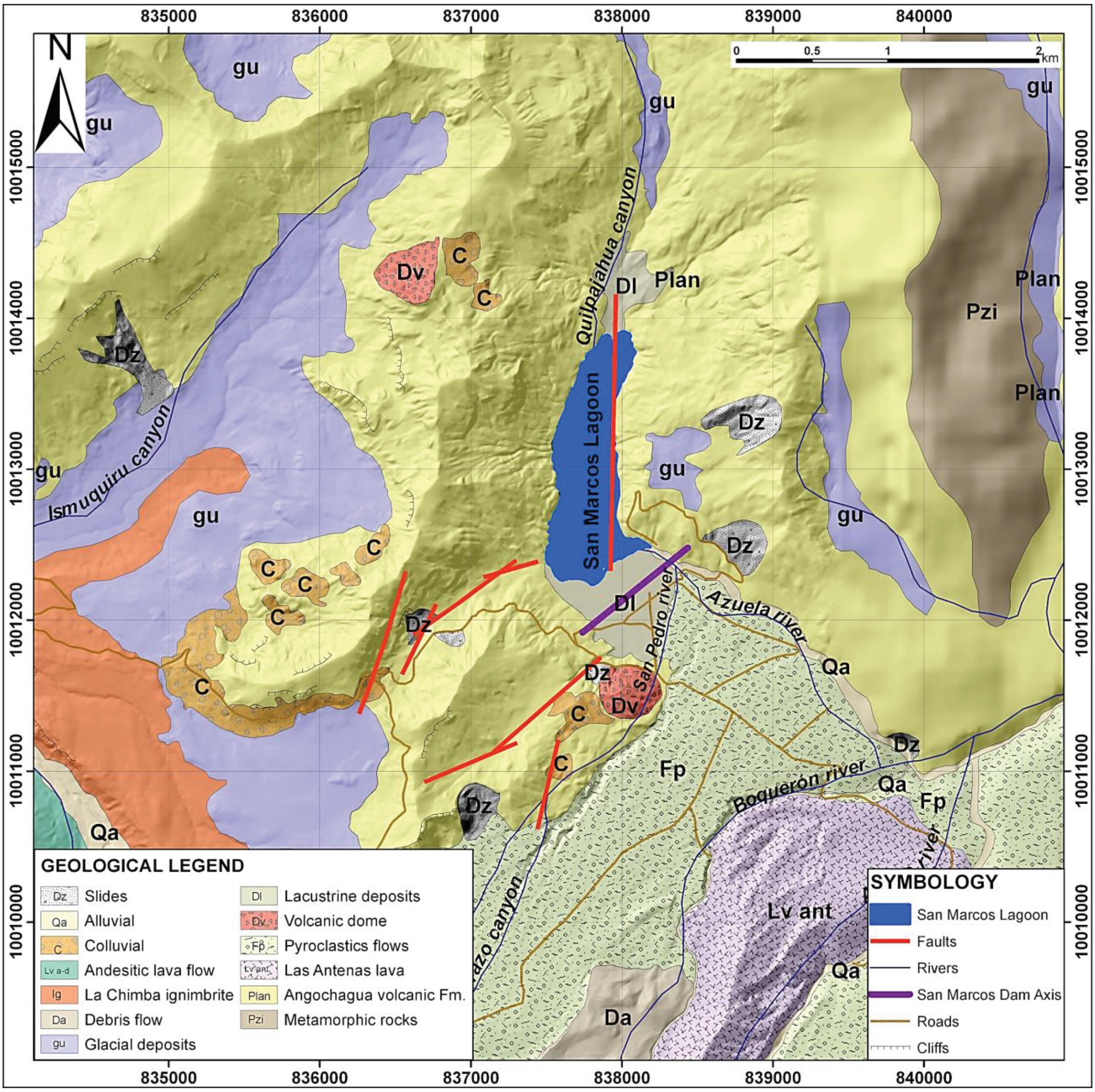

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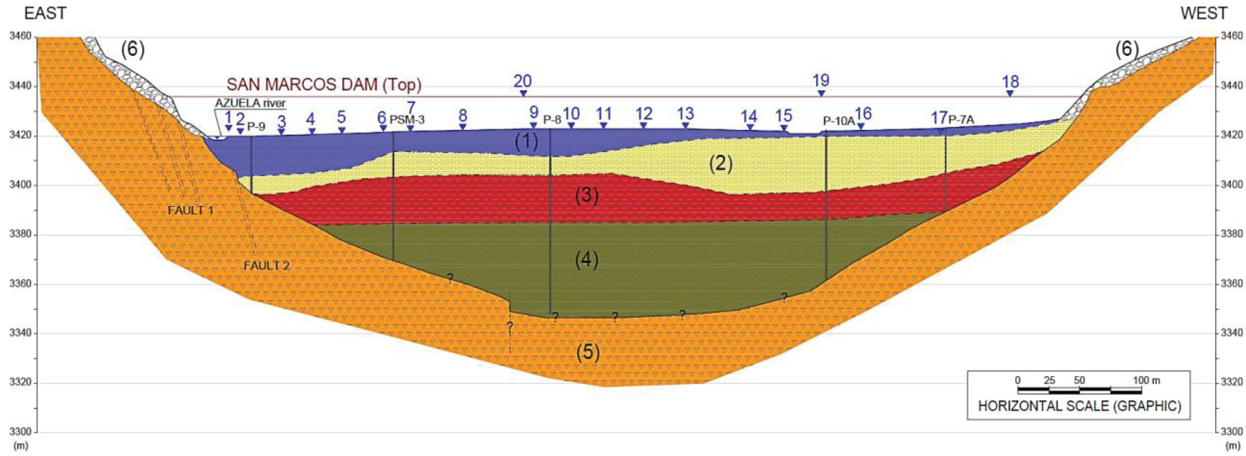

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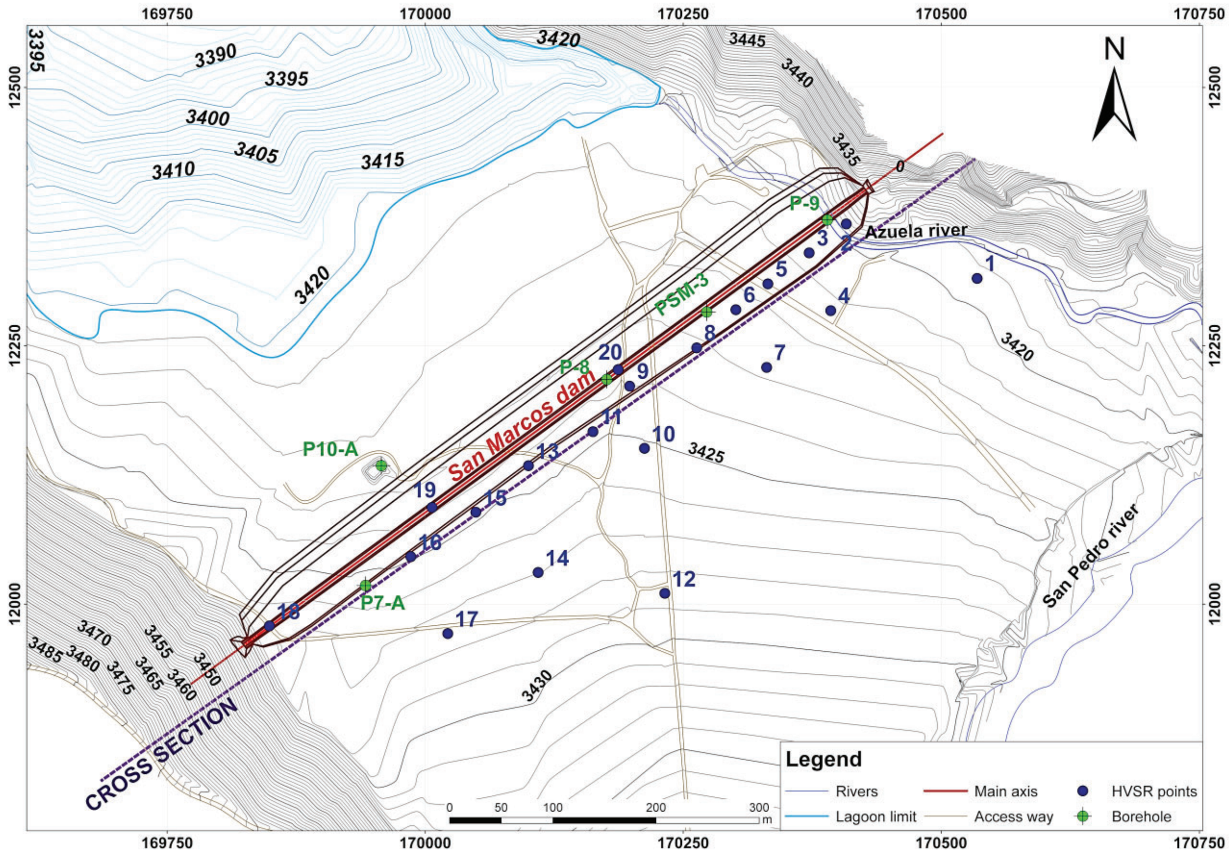

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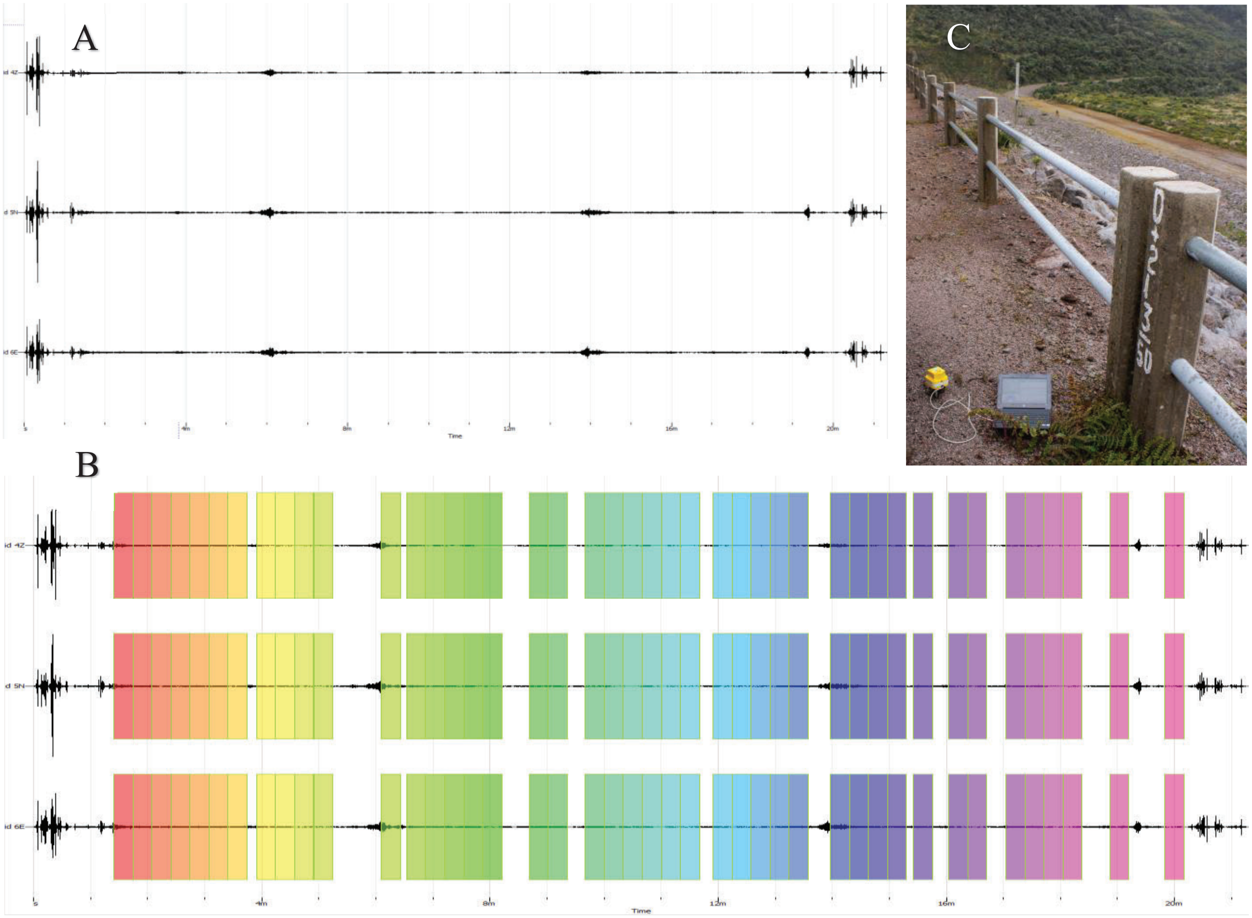

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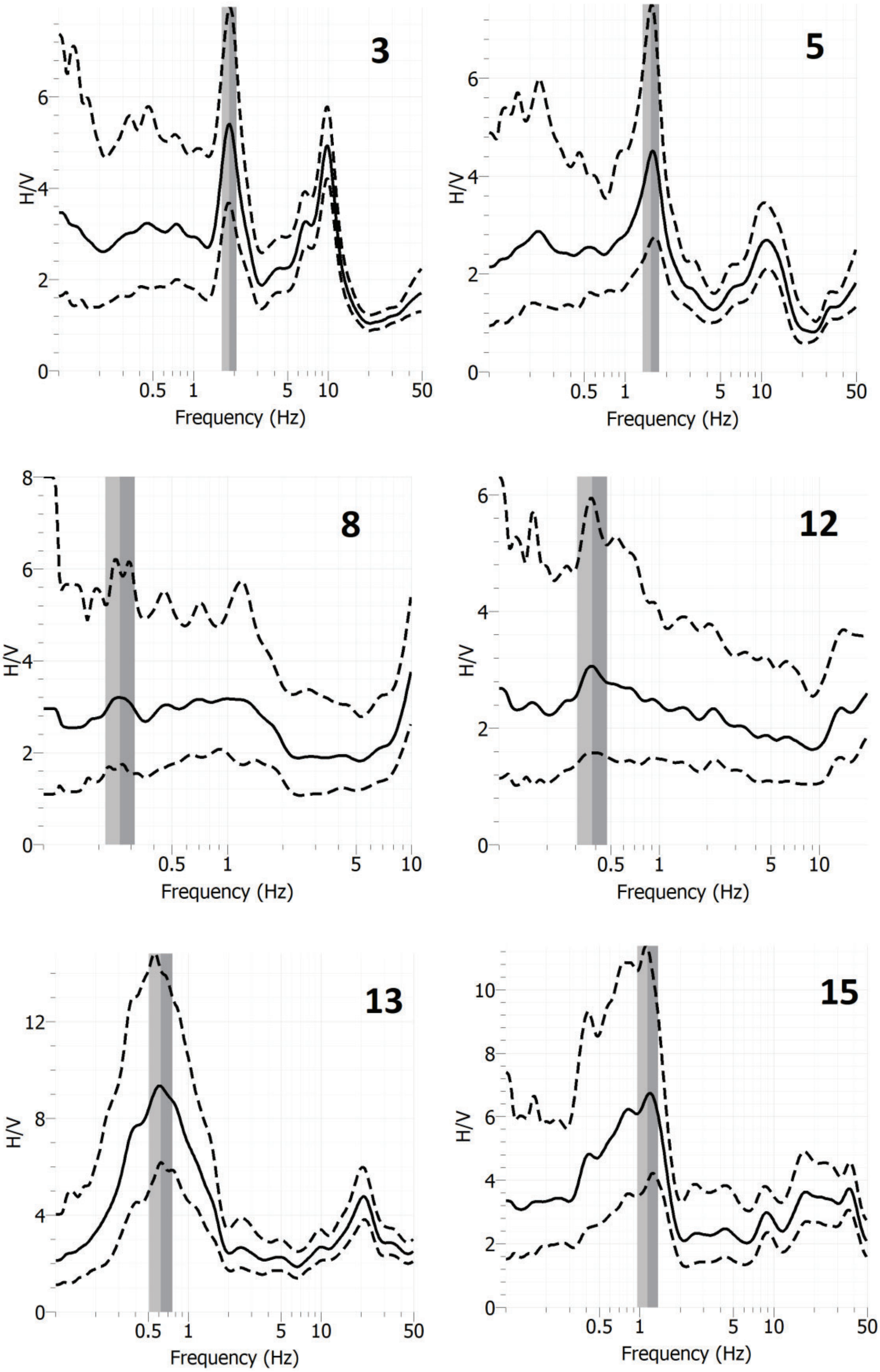

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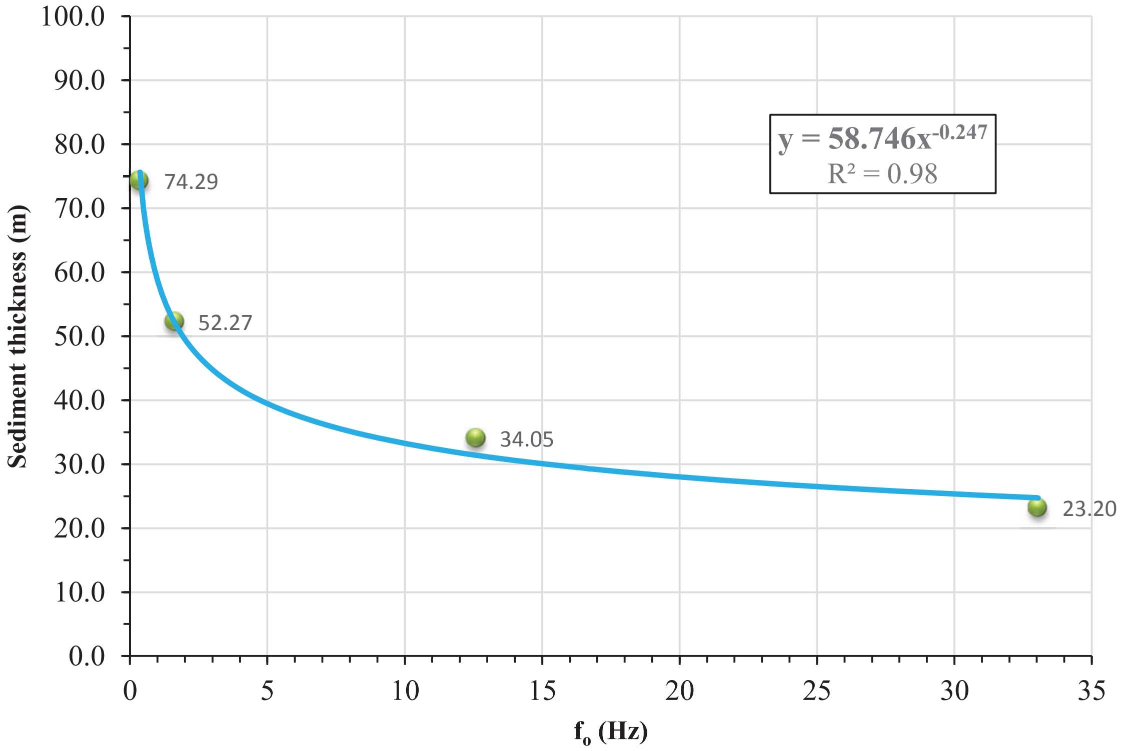

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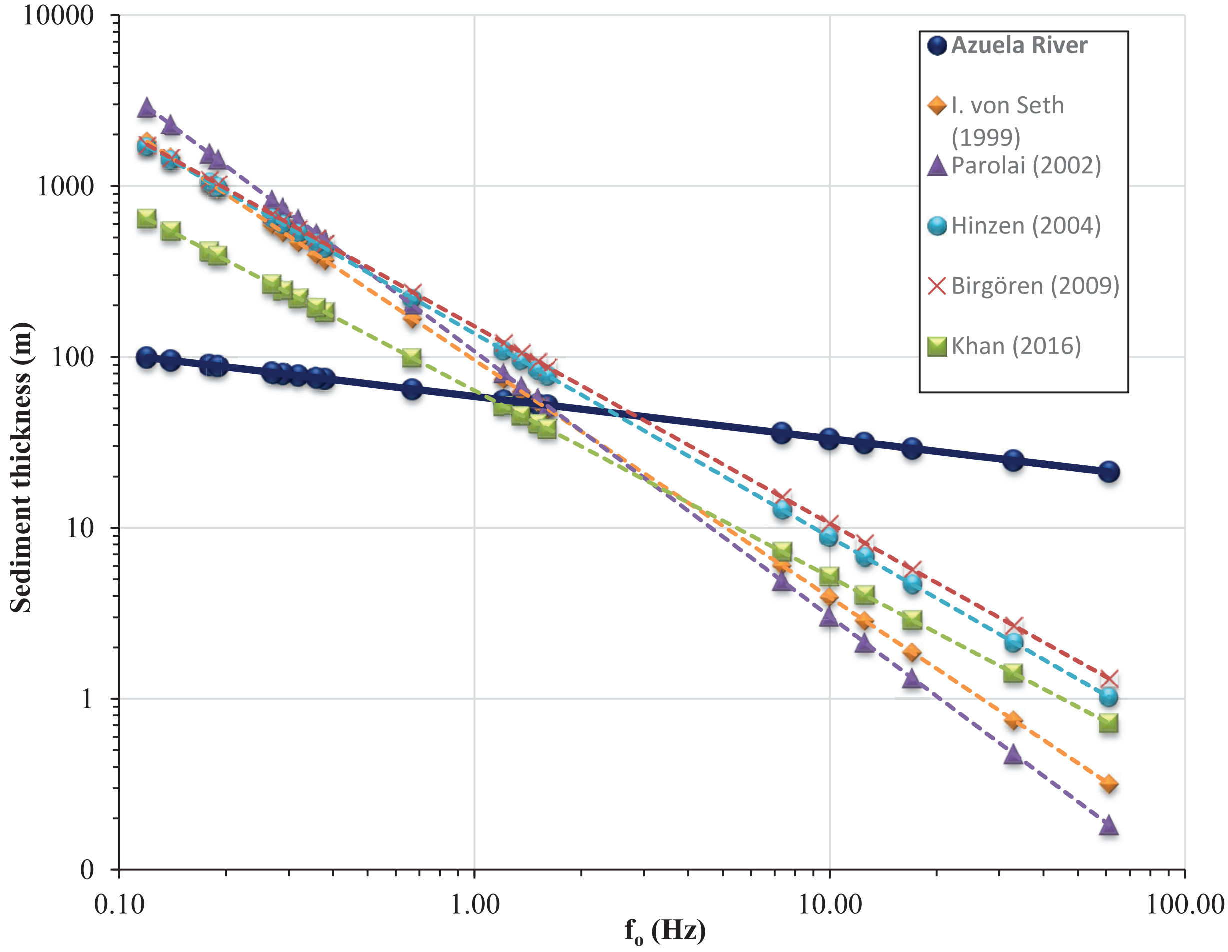

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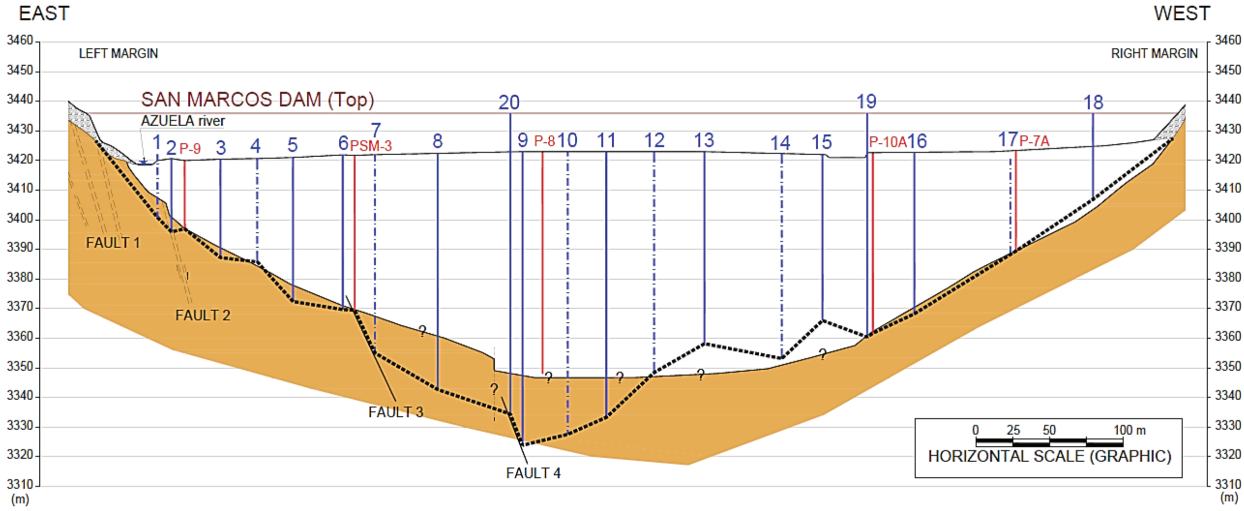

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Table

Table 1. Results obtained in present investigation with fundamental frequency (f_o), amplification (A_o) and period (T_o) of the 20 measured points.

POINT	f_o (Hz)	A_o	T_o (s)
1	*61.26*	1.90	0.02
2	*33.05*	3.45	0.03
3	*10.01*	4.94	0.10
4	*7.36*	1.58	0.14
5	*1.51*	4.92	0.66
6	*1.61*	3.70	0.62
7	*0.32*	1.65	3.13
8	*0.29*	3.36	3.45
9	*0.12*	3.10	8.33
10	*0.14*	3.31	7.14
11	*0.18*	2.14	5.56
12	*0.38*	2.81	2.63
13	*0.67*	8.74	1.49
14	*0.27*	9.33	3.70
15	*1.21*	5.35	0.83
16	*1.36*	5.17	0.74
17	*12.58*	4.49	0.08
18	*17.11*	7.42	0.06
19	*0.36*	2.37	2.78
20	*0.19*	3.61	5.26

Table

Table 2. Value of a and b coefficients to the equation defined by Bundy (1984) given by different authors, also including the present investigation. R2 obtained and materials where were performed are also indicated.

INVESTIGATION	*a*	*b*	R^2	MATERIALS
Ibs von Seth and Wohlenberg (1999)	96.000	-1.388	0.981	Sedimentary covers of Tertiary and Quaternary ages (Rhin River)
Parolai *et al.* (2002)	108.000	-1.551		Gravel, sand, and clays mainly
Hinzen *et al.* (2004)	137.000	-1.190		Well-sorted marine sand and consolidated clay (Rhin River)
Birgören *et al.* (2009)	150.990	-1.153	0.995	Dense sand, silty sand, clayey sand, gravel and clay
Khan and Khan (2016)	63.680	-1.090	0.990	Interbedded sandy silt and limestone gravel, aeolian loess
PRESENT STUDY	**58.746**	**-0.247**	**0.98**	**Alluvial and lacustrine sediments, volcanoclastic sediments and pyroclastic flows**

Table

Table 3. Refered boreholes with depth data of basement (in metres) and HVSR surveys performed as control correlation with fundamental frequency (fo)

BOREHOLE	BASEMENT	POINT	f_o
P - 9	23.20	**2**	33.05
PSM - 3	52.27	**6**	1.61
P - 7 A	34.05	**17**	12.58
P – 10 A	74.29	**19**	0.36

Table

Table 4. Depth of basement (bedrock) predicted by different authors equations (in metres) compared to the present investigation (third column) based on fundamental frequency f_0

HVSR POINT	f_o *(Hz)*	**THIS STUDY** (m)	**Ibs von Seth** (1999)	**Parolai** (2002)	**Hinzen** (2004)	**Birgören** (2009)	**Khan** (2016)
1	*61.26*	**21.3**	0.3	0.2	1.0	1.3	0.7
2	*33.05*	**24.8**	0.7	0.5	2.1	2.7	1.4
3	*10.01*	**33.3**	3.9	3.0	8.8	10.6	5.2
4	*7.36*	**35.9**	6.0	4.9	12.7	15.1	7.2
5	*1.51*	**53.1**	54.2	57.0	83.9	93.9	40.6
6	*1.61*	**52.2**	49.6	51.6	77.7	87.2	37.9
7	*0.32*	**77.8**	466.8	632.3	531.6	561.8	220.5
8	*0.29*	**79.8**	535.1	736.6	597.7	629.3	245.5
9	*0.12*	**99.2**	1821.2	2894.8	1708.0	1740.8	642.2
10	*0.14*	**95.5**	1470.4	2279.2	1421.8	1457.3	542.9
11	*0.18*	**89.7**	1037.4	1543.5	1054.3	1090.7	412.8
12	*0.38*	**74.6**	367.7	484.4	433.3	460.8	182.8
13	*0.67*	**64.9**	167.4	201.0	220.6	239.6	98.5
14	*0.27*	**81.2**	590.9	823.0	650.7	683.3	265.3
15	*1.21*	**56.0**	73.7	80.4	109.2	121.2	51.7
16	*1.36*	**54.4**	62.6	67.0	95.0	105.9	45.5
17	*12.58*	**31.4**	2.9	2.1	6.7	8.1	4.0
18	*17.11*	**29.1**	1.9	1.3	4.7	5.7	2.9
19	*0.36*	**75.6**	396.4	526.7	462.1	490.4	193.9
20	*0.19*	**88.5**	962.4	1419.3	988.6	1024.7	389.2

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Title Page

Highligths