Bedrock depth and shear wave velocity profile estimation through HVSR measurements in the Paraguayan oriental region

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ABSTRACT

The horizontal to vertical spectral ratio (HVSR) passive seismic method consists in processing measurements of ambient noise performed in three perpendicular directions. The objective is to define the primary resonant frequency of the site and estimate its amplification characteristics, which can be deduced from visible peaks or troughs in the HVSR curves. The shape of HVSR curves depend on the interaction of waves with the interface between sediments and the formation bedrock and, hence, can be related to the bedrock depth through derived relationships. This work presents 4 study cases in the Paraguayan oriental region where HVSR of microtremors were obtained. Furthermore, the obtained HVSR curves are inverted to get approximate shear wave velocity profiles under the assumption of sub-vertically propagating P and S body waves. HVSR curves were calculated through Geopsy (Wathelet et al. 2020) and the inversion process was made through OpenHVSR (Bignardi et al. 2016), both open-source tools for ambient vibration processing. In general, the method proves to give sufficient accurate estimates of sediment thickness and stratigraphy in typical Paraguayan formations of the oriental region and presents the advantage of being an economical and fast survey option, especially for early stages in a geotechnical campaign.

Keywords: HVSR; site characterization; shear wave velocity; ambient noise.

1. Introduction

The horizontal to vertical spectral ratio, HVSR or H/V, can be obtained from measurements of microtremors in three perpendicular directions performed through single station seismometers in the ground surface. The derived HVSR curves can be understood as the ratio of the horizontal ground motion spectra (usually from the squared average of the horizontal components) to the vertical ground motion spectra. The method was developed by (Nakamura 1989) that studied and theorized the characteristics of HVSR of microtremor and the reasons for its similarities with the horizontal amplification spectra of strong motion records. It allows the estimation of the fundamental frequency F_0 of the site and the amplification characteristics A_0 of the surface layers, that can then be related to the depth D of the bedrock.

Paraguay is considered as a low-seismicity country, being the most relevant seismic event a magnitude 5.2 mB earthquake that occurred in 1982 (Fugarazzo et al. 2021). Although there are some national complex engineering projects that may justify a seismic site classification and a site effect analysis, the main purpose of defining the HVSR of a site might generally be directed to an estimation of the substrate configuration for other engineering purposes. To this effect, the method presents the advantage of being an easy, fast, and low-cost survey option. However, the lack of use of seismic technology in our country and the limitations of the instruction in related knowledge areas constitutes a difficulty for its more widely implementation.

(Xu et al. 2021) summarized some setbacks and difficulties on the interpretation of HVSR of microtremor such as controversies on the physical explanation of results, the non-uniqueness of the substrate model solution and the dependence of the HVSR of microtremor on external factors like climate, topography, and source characteristics variations. Although, the HVSR of microtremor provides valuable information of the substrate, result interpretation must be done consciously and considering any previous geological information available of the site.

This paper presents 4 study cases in the Paraguayan oriental region where HVSR of microtremors were obtained and where some information of the subsurface characteristics was available. The main objective is to explain the characteristics of HVSR obtained through each known stratigraphy. Another expected outcome is to evaluate the possibility of direct application and validity of single layer models and inversion processes for the estimation of the subsurface configuration in terms of the shear wave velocity V_S and thickness of layers E_i.

Ambient noise measurements were performed following (SESAME 2004) guidelines with an Ambrogeo Echo Tromo HVSR 3 equipment. The recording duration of each measurement was of 30 minutes. Average HVSR curves, considering 25 seconds time windows, were calculated through Geopsy

(Wathelet et al. 2020) and inversion processes were made through OpenHVSR (Bignardi et al. 2016), both open-source tools for ambient vibration processing.

2. Theoretical framework

2.1. HVSR of microtremors

Although there are some different approaches on the explanation of the peak of the HVSR of microtremors, one of the most widely accepted is the one developed by (Nakamura 1989, 2008). Accordingly, the main assumptions of the method are listed below:

- The HVSR is approximately equal to one in the bedrock or hard substrate, because horizontal and vertical particle movement are known to be very similar.
- Under the presence of soft ground deposition over the hard substrate, amplification of motion occurs, being F_0 mainly caused by multiple reflections of SH waves.
- Vertical motion is caused by multiple reflection of P waves and has a fundamental frequency of about 5 to 20 times F_0. Around F_0 it is mainly affected by Rayleigh waves and can hence be used to eliminate its effect of the horizontal spectra, which is the main interest in a seismic site effect analysis context.

The transfer function of horizonal motion T_H and vertical motion T_V can be expressed as:

$$T_H = {}^{A_{HS}}/_{A_{HB}} \tag{1}$$

$$T_V = {}^{A_{VS}}/_{A_{VB}} \tag{2}$$

where A_{HS} and A_{VS} are the horizontal and vertical spectra of motion respectively at the surface, and A_{HB} and A_{VB} are the horizontal and vertical spectra of motion at the bedrock. The corrected transfer function of horizontal motion T_H' is then written as:

$$T_H' = {}^{T_H}/_{T_V} = {}^{A_{HS}}/_{A_{VS}} \div {}^{A_{HB}}/_{A_{VB}} \tag{3}$$

since ${}^{A_{HB}}/_{A_{VB}} \approx 1$, then

$$T_H' = {}^{A_{HS}}/_{A_{VS}} = HVSR \tag{4}$$

The most reliable information to be retrieved from HVSR curves is F_0. On the other hand, regarding the obtained amplification characteristics of the site, some authors (e.g. Bonnefoy-Claudet et al. 2008, Satoh et al. 2001, La Rocca et al. 2020) consider that they can be less representative, given the unknown exact composition of wave modes on ambient noise recordings and/or their possible dependence on factors that are not related to the stratigraphy.

2.2. HVSR inversion

Another application of the HVSR passive seismic method is the definition of the depth D of the bedrock and more extensively, the estimation of a shear wave velocity profile V_S. In both cases, it is necessary to have some initial preliminary information of the site's substrate.

Assuming a single layer model, in which a soft ground deposition lays over an infinite hard substrate, F_0 is related to D and its shear wave velocity V_{SS} in the following way (Paolucci and Faccioli 2002):

$$F_0 = {}^{V_{SS}}/_{(4 \times D)} \tag{5}$$

which allows the estimation of D if a value of V_{SS} is assumed. Furthermore, if densities of the bedrock and the soft ground are considered to be the same then (Nakamura 2008):

$$A_0 = {}^{V_{SB}}/_{V_{SS}} \tag{6}$$

then:

$$D = {}^{V_{SB}}/_{(4 \times A_0 \times F_0)} \tag{7}$$

which allows the estimation of D if a value of V_{SB} is assumed.

Various methods (e.g. Rong et al. 2016, Tian et al. 2020, Herak et al. 2008) have been proposed to obtain a more detailed V_S profile of the substrate through inversion processes of HVSR curves. The difference among them are the theoretical assumptions made. In this work the software OpenHVSR, written in MATLAB, has been used to invert the HVSR curves. The code has been developed by (Bignardi et al. 2016). It includes the formulation of (Herak et al. 2008) that proposed a Monte Carlo Inversion based on the formulations of (Tsai and Housner 1970). The method considers the assumption that HVSR peaks are generated by sub-vertically propagating P and S waves, and it requires the input of an initial model with thickness and visco-elastic information to improve the optimization of model parameters, given the non-uniqueness nature of results.

3. Description of selected sites

Table 1 indicates the UTM coordinates of each HVSR test position. All the sites are in the Paraguayan oriental region, as shown in Fig. 1. Bellow a brief geological description of each site is presented.

Table 1. UTM coordinates of HVSR tests.

HVSR Test positions			
Site	**X (m)**	**Y (m)**	**Z (m.a.s.l)**
San Lorenzo	443609	7195403	132
Piribebuy	496052	7183301	229
Itapúa	729396	7077272	114
Concepción	450284	7429760	96

Figure 1. Studied sites in the Paraguayan Oriental Region.

3.1. San Lorenzo

The first inspected site is in the city of San Lorenzo, in the Central Department. The geological formation is the one of the Patiño Aquifer and belongs to the Cretaceous Tertiary period. The formation is made up of conglomeratic sediments sandstones at the base and sandy sediments sandstones at the roof and has a strong red coloration. The minimum thickness of the formation is of 150 m on average.

3.2. Piribebuy

The city of Piribebuy belongs to the Paraguarí formation (Caacupé group) that corresponds to the Silurian period. It has coarse-grained sediments and conglomeratic layers that gradually transition to archosic sandstones. The unit has a thickness of approximately 20 m and lays over rocks from the Precambrian basement. In many places the conglomeratic layers are seen as outcrops, without any sandy sediments on the top.

3.3. Itapúa

The studied site is in the Carlos Antonio López district of the Itapúa department. The site lies over the Alto Paraná formation that belongs to the Cretaceous period. This area is constituted by an extensive area of basalt flow, predominantly tholeiitic. The thickness of the formation is estimated on 700 m to 800 m on average.

3.4. Concepción

The city of Concepción is located over the San Antonio formation that belongs to the Quaternary period. The formation is constituted by a light-colored sandstone of medium to coarse granulation with scattered gravel, interspersed with shale. There are also layers of clayey sandstones up to 1.5 meters thick. The sedimentation environment is fluvial.

4. Results and analysis

4.1. San Lorenzo

Fig. 2 and Fig. 3 show the HVSR results for the San Lorenzo site, the Standard Penetration Test profile (N_{60} values) of reference and the subsurface stratification, up to a depth of 30 m.

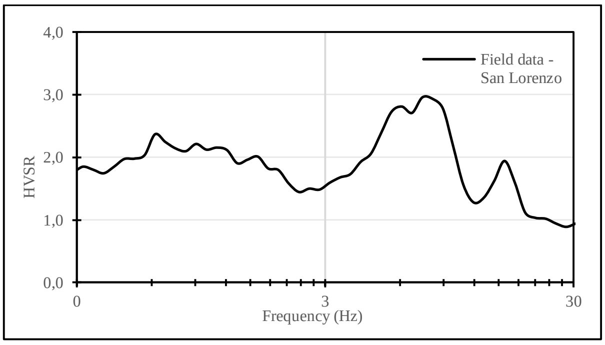


Figure 2. HVSR field data from the San Lorenzo site.

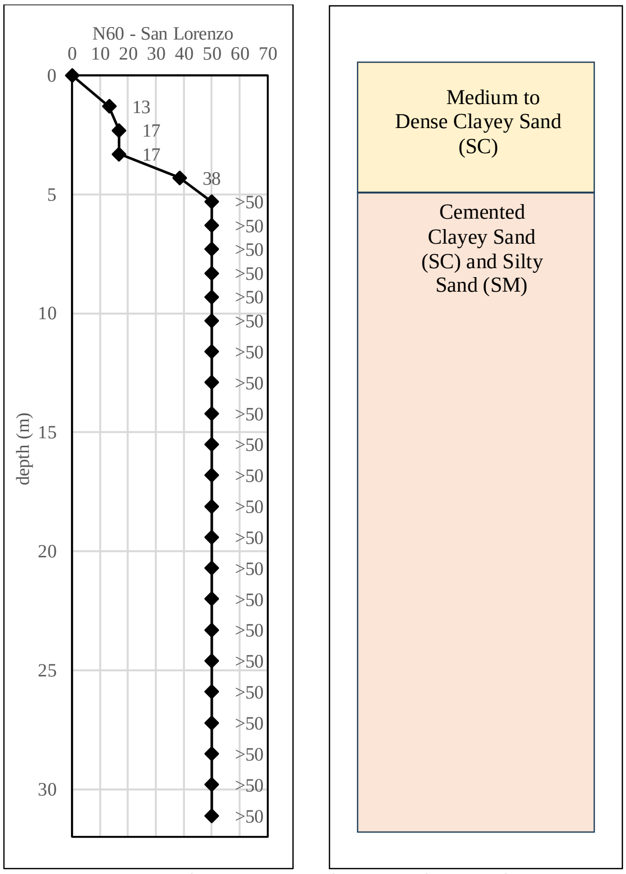


Figure 3. SPT profile and subsurface stratification for the San Lorenzo site.

4.1.1. Single layer model

The HVSR exhibits a F_0 =7.4 Hz and an A_0=2.95. In a single layer model and considering a V_{SB}=610 m/s for heavily cemented sands or soft rocks, known to be present in the site, the approximate value of the depth of the bedrock D=6.99 m, according to Eq. (7).

The relatively small amplitudes suggest the contrast impedance is moderately low, which agrees with the expected stratigraphy of a moderate increase of density of the formation with depth. A lower peak is seen at F=0.68 with A_0=2.24, which may indicate a possible transition to a deeper and sounder formation.

4.1.2. OpenHVSR inversion

OpenHVSR requires an initial model with thickness and visco-elastic information. The model parameters for each considered layers are V_p, V_s, ρ, E, Q_p, Q_s, where V_p is the compressional wave velocity, ρ is the soil's density and Q_p and Q_s are the compressional and shear damping parameters respectively. The parameters are defined based on the single layer model and considering the equations listed below for the sediments layer:

$$V_s = 56.4 \times {N_{60}}^{0.5} \text{ (Seed et al. 1983)} \quad (8)$$

$$V_p = 1.16 \times V_s + 1.36 \text{ (Castagna 1985)} \quad (9)$$

$$\rho = 0.77 \times log_{10}(V_s) + 0.1 \text{ (Dal Moro et al. 2007)} \quad (10)$$

$$Q_s \approx {}^{V_s}/_{6} \text{ and } Q_p \approx 2 \times Q_s \text{ (Dal Moro 2010)} \quad (11)$$

Eq. (8) is used with values extracted or inferred from nearby N_{SPT} soil profiles and geological knowledge of the area. As for the bedrock properties, the same V_{SB} is considered as in the single layer model, while the thickness and damping parameters are set as very large values to indicate infinite properties. The initial model parameters are listed in Table 2.

Table 2. Initial model of the San Lorenzo site.

Layers	Vp (m/s)	Vs (m/s)	ρ (kN/m3)	E (m)	Qp	Qs
Layer 1	254.74	218.4	18.2	6.99	53.2	26.6
Layer 2	708.96	610	22.6	999	999	999

The inversion process consisted in firstly limiting the analysis to the frequencies that surround the main peak in the spectra, considering a single layer model, with a 25% perturbation of parameters and 5,000 iterations. Afterwards, the infinite layer was subsequently divided in more layers and the frequency range of analysis was increased. In the last step a 5% perturbation was allowed for 10,000 iterations.

Fig. 4 and Fig. 5 show the results of the inversion process for the San Lorenzo site. Results can be considered relatable to the existing geotechnical and geological information, with a first strong change of impedance at around 6 m and relatively even properties up to a depth of around 200 m.

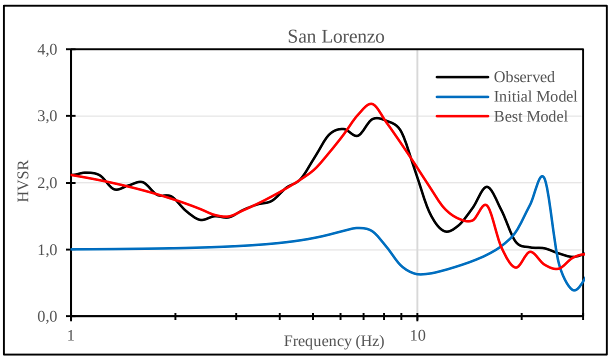


Figure 4. HVSR inverted results for the San Lorenzo site.

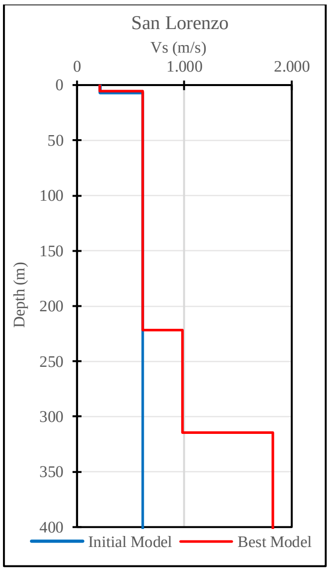


Figure 5. Vs profile, initial and inverted model for the San Lorenzo site.

4.2. Piribebuy

Fig. 6 and Fig. 7 show the HVSR results for the Piribebuy site, the RQD% (Rock Quality Designation) profile of reference and the subsurface stratification, up to a depth of 30 m.

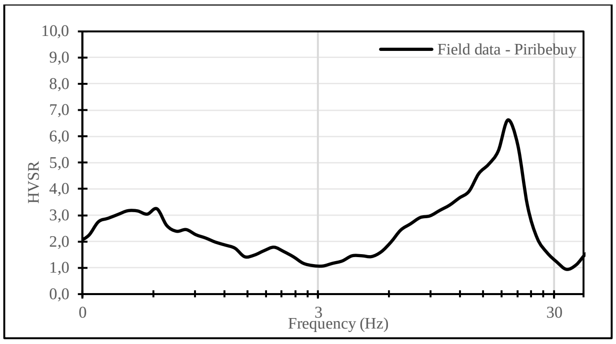


Figure 6. HVSR field data from the Piribebuy site.

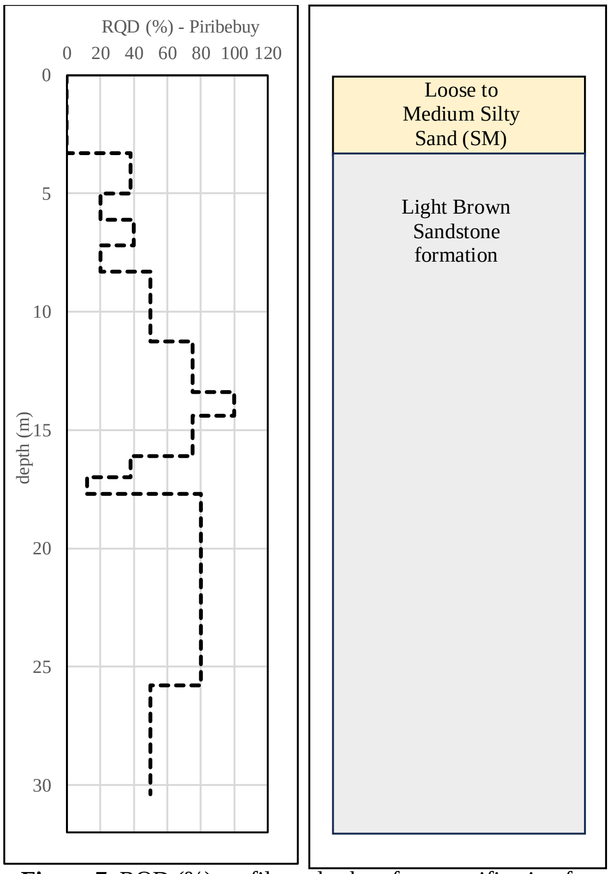


Figure 7. RQD (%) profile and subsurface stratification for the Piribebuy site.

4.2.1. Single layer model

The HVSR exhibits a F_0 =19.19 Hz and an A_0=6.62. The signal amplitude indicates a strong impedance contrast. In a single layer model and considering a V_{SB}=1300 m/s for sound continuous sandstones formations, the approximate value of the depth of the bedrock D=2.56 m, according to Eq. (7). A lower peak is seen at F=0.68 with A_0=2.6, which can indicate another, but more moderate, impedance change in stratigraphy.

4.2.2. OpenHVSR inversion

The same procedure described in section 4.1.2. has been considered. The initial model parameters for this site are listed in Table 3.

Table 3. Initial model of the Piribebuy site.

Layers	Vp (m/s)	Vs (m/s)	ρ (kN/m³)	E (m)	Qp	Qs
Layer 1	208.3	178.4	18.8	2.56	59.5	29.7
Layer 2	1509	1300	25.5	999	999	999

Fig. 8 and Fig. 9 show the results of the inversion process for the Piribebuy site. Results show a first strong change of impedance at around 1.19 m and little change of properties with depth from that point on.

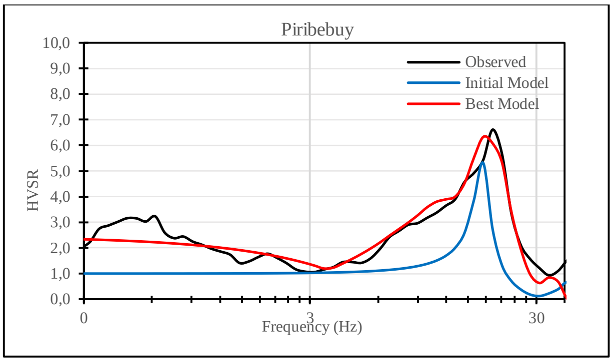


Figure 8. HVSR inverted results for the Piribebuy site.

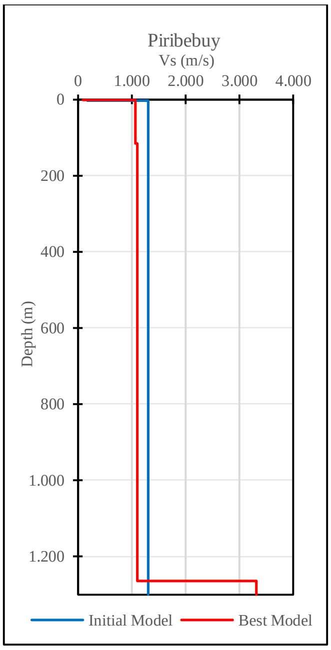


Figure 9. Vs profile, initial and inverted model for the Piribebuy site.

4.3. Itapúa

Fig. 10 and Fig. 11 show the HVSR results for the Itapúa site, the RQD% (Rock Quality Designation) profile of reference and the subsurface stratification, up to a depth of 30 m.

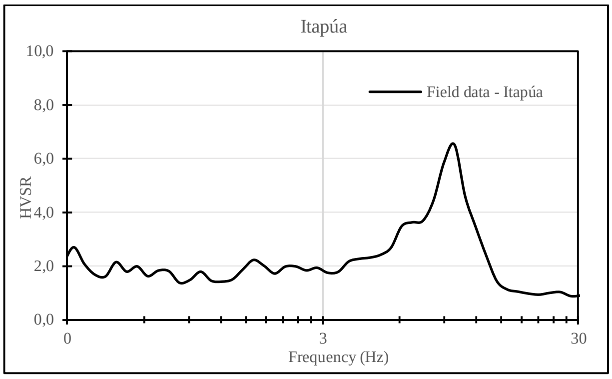
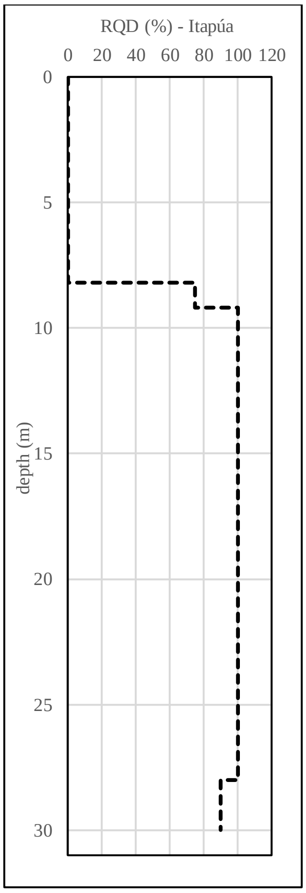


Figure 10. HVSR field data from the Itapúa site.



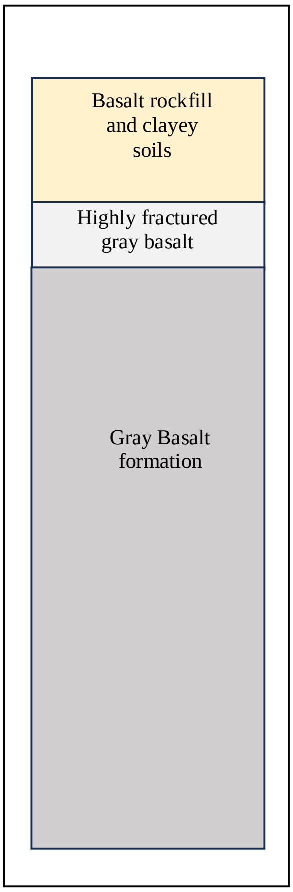


Figure 11. RQD (%) profile and subsurface stratification for the Itapúa site.

4.3.1. Single layer model

The HVSR exhibits a F_0 =9.84 Hz and an A_0=6.51. The signal amplitude indicates a strong impedance contrast. In a single layer model and considering a V_{SB}=2000 m/s for sound continuous basalt formations, the approximate value of the depth of the bedrock D=7.81 m, according to Eq. (7).

4.3.2. OpenHVSR inversion

The same procedure described in section 4.1.2. has been considered. The initial model parameters for this site are listed in Table 4.

Table 4. Initial model of the Itapúa site.

Layers	Vp (m/s)	Vs (m/s)	ρ (kN/m³)	E (m)	Qp	Qs
Layer 1	465.4	400	21.5	7.81	133.3	66.7
Layer 2	2321.4	2000	25.0	999	999	999

Fig. 12 and Fig. 13 show the results of the inversion process for the Itapúa site. Results show a first strong change of impedance at around 7.19 m and little change of properties until up to around 1005 m. Results can also be considered relatable to the existing geotechnical and geological information.

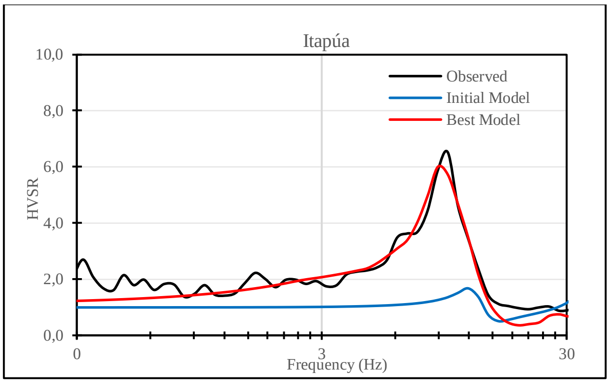


Figure 12. HVSR inverted results for the Itapúa site.

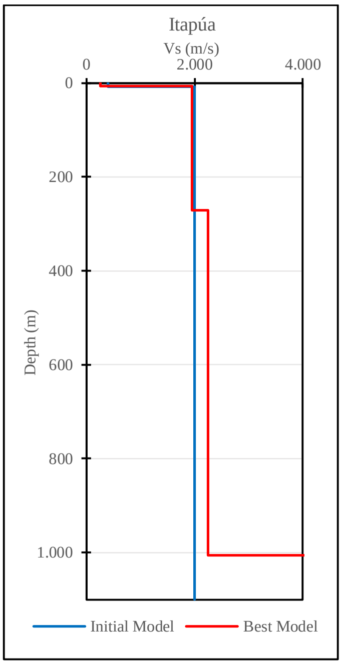


Figure 13. Vs profile, initial and inverted model for the Itapúa site.

4.4. Concepción

Fig. 14 and Fig. 15 show the HVSR results for the Concepción site, the Standard Penetration Test profile (N_{60} values) of reference and the subsurface stratification, up to a depth of 30 m.

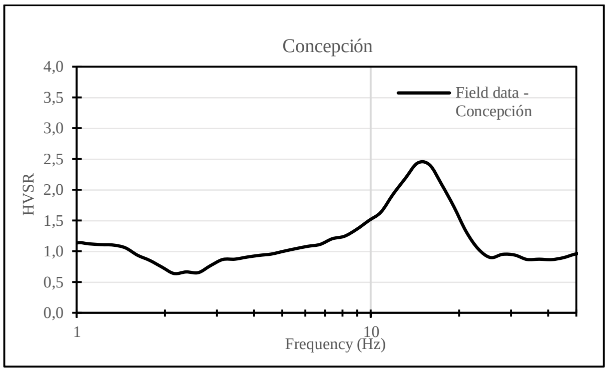


Figure 14. HVSR field data from the Concepción site.

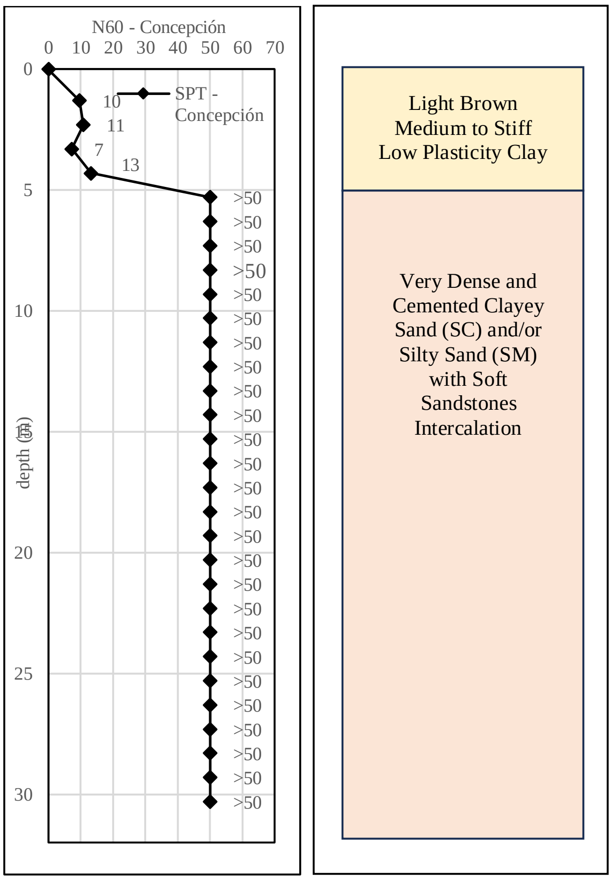


Figure 15. SPT profile and subsurface stratification for the Concepción site.

4.4.1. Single layer model

The HVSR exhibits a F0 =14.4 Hz and an A0=2.43. In a single layer model and considering a V_{SB}=600 m/s for heavily cemented sands or soft rocks, the approximate value of the depth of the bedrock D=4.28 m, according to Eq. (7).

The small amplitudes suggest the contrast impedance is moderately low, which agrees with the expected stratigraphy that presents very small changes with depth.

4.4.2. OpenHVSR inversion

The same procedure described in section 4.1.2. has been considered. The initial model parameters for this site are listed in Table 5.

Table 5. Initial model of the Concepción site.

Layers	Vp (m/s)	Vs (m/s)	ρ (kN/m³)	E (m)	Qp	Qs
Layer 1	233.4	200	19.2	4.28	66.7	33.3
Layer 2	697.4	600	23.0	999	999	999

Fig. 16 and Fig. 17 show the results of the inversion process for the Concepción site. Results show a first moderate change of impedance at around 2.58 m and another one at 90.1 m. The inverted profile shows relatively constant properties until a depth of around 300 m.

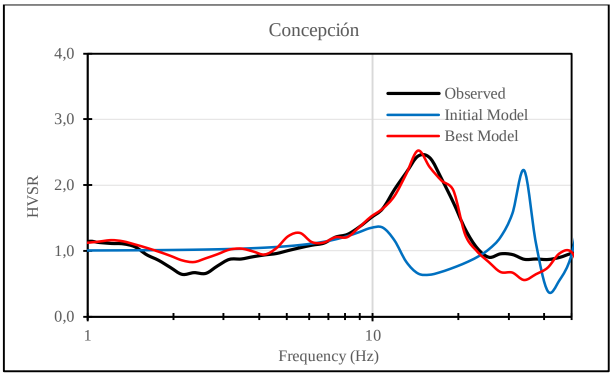


Figure 16. HVSR inverted results for the Concepción site.

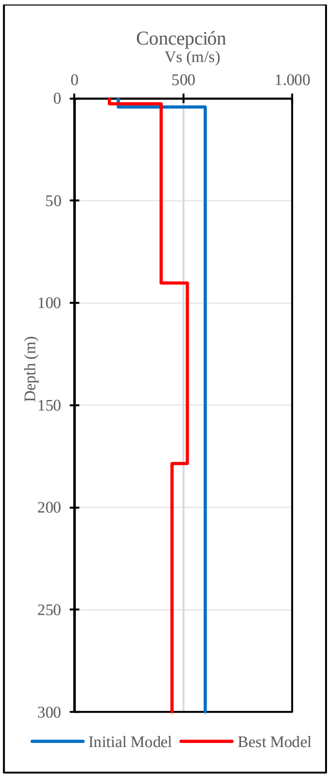


Figure 17. Vs profile, initial and inverted model for the Concepción site.

5. Conclusions

This work aimed to present the workflow of inferring some basic aspects of the subsoil configuration from the HVSR of microtremors. Although the method was mainly directed towards the estimation of the seismic site classification and seismic site effect analysis, the obtained information can be used for other civil engineering purposes. For instance, the definition of a bedrock depth position can be of interest for many projects, as well as the definition of continuity of certain formations with depth and/or a general geological characterization for initial recognition works.

The single layer model can be used for determining the bedrock depth in a practical way if basic properties of the bedrock are known. From this experience, it can be concluded that this procedure gives good estimates of *D*, especially for shallow depths and for a high impedance contrast. For deeper formations and lower impedance contrasts the precision of results tend to decrease.

The inversion of HVSR of microtremors with OpenHVSR can provide additional and more detailed information than the single layer model. However, the process requires specific technical knowledge and the insertion of an initial model, which can sometimes result inconvenient. The best fitted frequency range is that around the fundamental peak, in opposition to the lower and higher frequency range that might be less representative. Therefore, shallower, or deeper stratigraphy changes than the one which generates the fundamental peak, must be taken more cautiously.

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