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Seismic soil classification for tropical residual soils using non-destructive geophysical methods and SPT blow count correlations.

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***Abstract*– Earthquakes are responsible for a significant amount of money losses and death tolls. For this reason, their force is considered in civil engineering designs. The first method that implemented earthquake effects was descriptive structural design, later a performance-based seismic structural design methodology was developed. The latter considers the dynamic properties of the soil. An important factor for appropriate implementation of this methodology is the seismic site classification. The site classification can be estimated with the help of destructive geotechnical tests, such as SPT, CPT, PMT, together with statistical correlations. However, it can also be determined by using non-destructive testing (i.e. geophysical testing). These estimations can be made obtaining the average shear-wave velocity in the upper 30 m and the fundamental frequency of the soil. In this study a comparison between the results obtained from refraction microtremor (ReMi) and Horizontal-to-Vertical Spectral Ratio (HVSR) geophysical tests against existing engineering correlations based on SPT tests was developed. The soils tested correspond to tropical residual soils, from Panama City. Results show that the ReMi and HVSR tests in combination accurately represent the properties of the soil. Also, this study identifies which correlations are best suited to be used in residual soils similar to the studied site.**

***Keywords*—shear-wave velocity, fundamental frequency, site classification, performance-based design, correlations.**

I. Introduction

Natural disasters occur with the presence of an extreme natural phenomenon, which is mostly unpredictable. Their impact depends on many factors according to the event; however, measures can be implemented to try to mitigate the damage and negative effects on the population.

Particularly earthquakes, which are the result of energy release from the interior of the planet, are one of the most dangerous natural disasters that a society can experience. This phenomenon is represented by ground shaking, which historically are responsible of great death and economic tolls [1].

Though earthquakes can be a secondary effect of volcanic eruptions or human activities on the surface or subsurface, they are mainly stimulated by active tectonic movements. Meaning earthquakes frequently occur at the plate boundaries (seismic belts) and at existing faults [2].

Technically, small magnitude earthquakes (< 2 Moment magnitude scale) occur worldwide about hundreds of times a day [3]; but they are not easily perceived. On the other hand, bigger earthquakes occurrence, as well as their impact, varies depending on different aspects, such as the focal depth, epicenter distance and local site conditions.

Over time many devastating earthquakes have triggered researchers' curiosity on how to prevent as many deaths and economics losses as possible due to structural failures. Some of the important events that pushed forward the earthquakes force consideration on the existent structural codes are the 1923 Great Kanto earthquake in Japan, and the 1933 Long Beach earthquake in the US [4].

Nowadays, the design codes have improved based on the performance of their minimum requirements during past seismic events. Engineering codes initially based their requirements on prescriptive design methodology. However, it was encountered that even though buildings with this type of design respond satisfactorily to earthquakes, there was significant damage to structures. Which resulted in high costs of repair, or even loss of use [5].

Consequently, a new philosophy of design was developed in the early 90s [6], the Performance-Based Earthquake design, or performance-based seismic design (PBSD). Some documents that lead off this concept were SEAOC Vision 2000, ATC 40 and FEMA 273 ab 274 [5].

The main difference between prescriptive design and PBSD is that the first focuses on strength, ductility and serviceability drift limits; and the latter makes emphasis on performance objectives related to buildings damages.

In Panama, PBSD concept was firstly slightly incorporated in the 2014 Structural Panamá Regulation, REP, from the Spanish "Reglamento Estructural de Panamá" [7]. Nevertheless, it is not until the 2021 update that a PBSD procedure was incorporated [8].

When applying PBSD it is important to reduce at minimum all possible errors. Otherwise the accuracy of the method can be compromised. One of the important parameters for the correct usage of PBSD is the site classification of the structure [9]. Its importance relies on the fact that it categorizes the soil's dynamic behavior.

Getting to know the soil´s dynamic behavior for PBSD is essential because the ground motions propagate differently according to the geotechnical and geological local conditions. Meaning that if, hypothetically, a same ground motion occurs in two completely different local conditions, the damage and soil response will be different as well.

The process of seismic site classification consists of analyzing the upper 30 m of the soil [10]. Some suitable parameters for making this classification are the fundamental vibration period/frequency, and the average shear wave velocity.

The aforementioned characteristics can be estimated directly by high-cost tests such as: downhole and crosshole test. Conversely, less expensive tests such as Horizontal-to-Vertical Spectral Ratio (HVSR), and Refraction of Microtremor (ReMi) can be used.

In addition, regarding the shear-wave velocity, some research has been conducted to generate correlations between it and Standard Penetration test results [11], [12].

The aim of this study is to estimate the fundamental vibration frequency and average shear-wave velocity of the upper 30 m soil of a specific site area with different methodologies, including destructive geotechnical tests and passive geophysical testing. This will enable the selection of the most appropriate correlations to be used in residual soils similar to those in the site of study.

II. AREA OF STUDY

This study was specifically carried out in Panama, inside the campus Dr. Victor Levi Sasso of the Technological University of Panama (UTP). Located at the jurisdiction of Ancon at Panama City.

Panama is an active seismic country that forms part of the Panama microplate. It is surrounded by the tectonic plates of Coco, Nazca, Caribbean and South America. The two zones with high seismicity vulnerability are Chiriqui due to the Panama Fracture Zone and the Panama City due to the location of the faults of Limon and Pedro Miguel. However, the latter has not caused damaging earthquakes for over 100 years [13].

In general, Panama´s geology is diverse. The great majority of the studies have been done for oil, mining and geological industries purposes. These studies are compiled in a map that represents the existence of formations from the Quaternary, Tertiary and Secondary era [14].

However, the geological characterization made by Steward et al are represented in [15], which demostrates that the specific area of analysis of this study corresponds to formations of intrusive and extrusive basalt from the middle and late Miocene (Fig. 1).

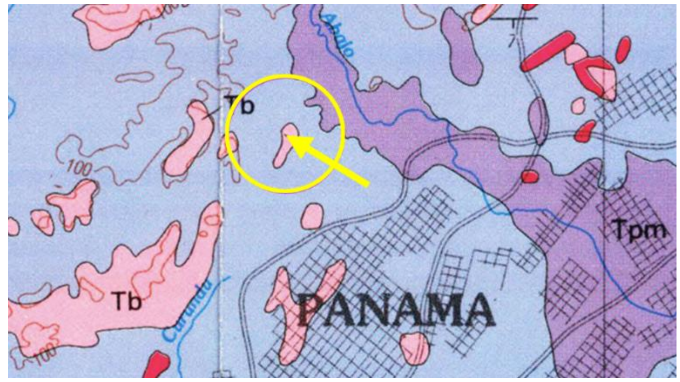

Fig. 1 Project location in the Geologic map of (Stewart et al. 1980)

III. RESEARCH METHODOLOGY

First, the area where the tests were going to be carried out was selected as such as that they could be done near an accelerograph station (Fig. 2). This test site was chosen; so, that the soil features of all source data would be the same.

A geotechnical boring was performed, together with two geophysical tests based on environmental noise: Horizontal-to-Vertical Spectral Ratio (HVSR) and Refraction Microtremor (ReMi).

Alongside, existing correlations were analyzed to estimate theoretically the fundamental frequency and shear wave velocity of the site.

Fig. 2 Project location (yellow line: alignment of the geophones; red dot: accelerograph; blue dot (borehole).

A. *Geotechnical investigation*

For this study, a borehole of at least 30.0 m is needed to categorize correctly the soil profile. Rotary drilling was performed by using ML Series TMG Drilling (Fig. 3). Samples were taken every 1 m, until rock was encountered. Standard Penetration Testing (SPT) were developed each meter of depth. A lining tube was placed to prevent the collapse of the borehole. Rock samples were extracted with a diamantine socket rock corer (Fig. 4). Afterwards, the samples are taken to the laboratory for further analysis.

Fig. 3 Logging with TMG Drilling from the ML series.

Fig. 4 Rock specimens

B. Horizontal-to-Vertical Spectral Ratio Methodology (HVSR)

This methodology is a passive geophysical test that estimates the fundamental frequency of a soil surface layer from microtremor analysis by a series of transfer functions.

It is based on the concepts developed by Nakamura, who proposes that the transfer function (S_{TT}) of the surface layer may be estimated just with the surface ratio (S_{HS}/S_{VS}). Because it was encountered, the subsurface ratio tends to be one ($S_{HB}/S_{VB} = 1$), meaning that the wave propagation is mostly even in all directions in the subsurface region [16].

$$S_{TT} = \frac{S_{HS}/S_{VS}}{S_{HB}/S_{VB}} = \frac{S_{HS}/S_{VS}}{1} \quad (1)$$

The result of this analysis is a frequency-domain graph versus the H/V ratio, which at its peak represents the fundamental frequency of the soil [17]. This parameter is later used to classify the site according to the method proposed by [17,18], shown in Table I.

TABLE I
DEFINITION OF SITE CLASSIFICATION ACCORDING TO [18]

Site/Class	Natural Period (s)	Predominant Frequency (Hz)
SC I: rock/stiff soil	$T_G < 0.2$	$f_0 > 5$
SC II: rigid soil	$0.2 \leq T_G < 0.4$	$2.5 \leq f_0 < 5$
SC III: semi-rigid soil	$0.4 \leq T_G < 0.6$	$1.6 \leq f_0 < 2.5$
SC IV : soft soil	$T_G \geq 0.6$	$f_0 \leq 1.6$

C. Refraction Microtremors methodology (ReMi)

Like the HVSR, this methodology also uses environmental noise and it is a passive geophysical test. Only that the result of this analysis is a one-dimensional shear-wave velocity profile.

It is based on two fundamental ideas [19]:

1. The arrangement of the equipment as an alignment allows us to acquire data from the superficial waves up to 2 Hz.
2. The transform slow-frequency function of a microtremor allows to separate the Rayleigh waves from the other ones, to recognize the real phase velocity from the apparent.

Despite the increase in popularity of this method, it is important to note that it is not reliable on its own. It should be compared with other analysis, such as the Nakamura method.
Also, from this analysis, the average shear wave velocity up to 30 m is obtained and used to classify the site according to the NEHRP (Table II).

TABLE II
TYPE OF SOIL PROFILE CLASSIFICATION ACCORDING TO NEHRP BASED ON THE AVERAGE SHEAR WAVE RATE UP TO 30 m

Soil type	General Description	V_{s30} (m/s)
A	Hard rock	$V_{s30} > 1500$
B	Rock	$760 < V_{s30} \leq 1500$
C	Hard and/ or very stiff soil	$360 < V_{s30} \leq 760$
D	Rigid soils	$180 < V_{s30} \leq 360$
E	Semi-rigid soils	$V_{s30} < 180$
F	Soils that require specific calculations	Does not apply

D. Correlation equations

In a study the Pacific Earthquake Engineering Research (PEER) "Guideline for Estimation of Shear Wave Velocity Profiles" is taken as a reference for the soil layers. As in this study, the geotechnical study for soil layers was a SPT. The equations that are considered are the uncorrected N_{SPT} for the applicable type of soil, based on (2), (3), (4) [20]. (Table III)

$$V_s = a \cdot N^b \quad (2)$$

$$V_s = a \cdot (N+1)^b \quad (3)$$

$$V_s = a \cdot (N+0.33)^b \quad (4)$$

TABLE III
N_{SPT} CORRELATIONS [20]

Soil type	Method	Geologic age	a	b	Eq.
All Soils	Ohba & Toriuma (1970)	-	85.3	0.31	(2.1)
	Ohsaki & Iwasaki (1973)	-	81.4	0.39	(2.2)
	Ohta & Goto (1978)	Q	85.3	0.35	(2.3)
	Ohta & Goto (1978)	H	92.2	0.27	(2.4)
	Ohta & Goto (1978)	P	134.2	0.27	(2.5)
	Imai & Tonouchi (1982)	H, P, T	97.0	0.31	(2.6)
	Imai & Tonouchi (1982)	T	109.0	0.32	(2.7)
	Lin et al. (1984)	-	65.6	0.50	(2.8)
	Sisman (1995)	-	32.8	0.51	(2.9)
	Iyisan (1996)	-	51.5	0.52	(2.10)
	Jafari et al. (1997)	-	22.0	0.85	(2.11)
	Kiku et al. (2001)	-	68.3	0.29	(2.12)
	Hasncebi & Ulusay (2007)	Q	90.0	0.31	(2.13)
Clay	Ohta & Goto (1978)	Q	85.6	0.34	(2.14)
	Ohta & Goto (1978)	H	93.1	0.25	(2.15)
	Ohta & Goto (1978)	P	134.8	0.25	(2.16)
	Imai & Tonouchi (1982)	H	98.4	0.25	(2.17)
	Imai & Tonouchi (1982)	H	107.0	0.27	(2.18)
	Imai & Tonouchi (1982)	P	128.0	0.26	(2.19)
	Lee (1992)	H	138.4	0.24	(3.1)
	Pitilakis, et al. (1999)	Q	132.0	0.27	(2.20)
	Jafari et al. (2002)	-	27.0	0.73	(2.21)
	Hasncebi & Ulusay (2007)	Q	97.9	0.27	(2.22)
Silt & Clay	Jinan (1987)	H	116.1	0.20	(4.1)
	Lee (1992)	H	129.4	0.26	(4.2)
Geologic Age: H=Holocene, P=Pleistocene, Q=Quaternary, T=Tertiary					

For the layers of rock, the PEER guideline presents methodologies based on existing data typical from the US. Because Panama´s characteristics are different, the proposed methods cannot be applied without prior validation.

Hence, (5) proposed by [21] is used to estimate the shear wave velocity according to the compressional wave velocity (V_P) of volcanic rocks. Taking as a basis the aforementioned equation, (6) from [22] is used for estimation V_P.

$$V_S = 0.937562 V_P^{0.81846} \quad (5)$$

Where V_S and V_P are in kft/s.

$$V_P = 67.683\rho_w - 875.91 \quad (6)$$

The equation proposed by [22] was chosen due to the similar geochronological, geochemical and isotopic characteristics from the arc related rocks from Panama and Colombia [23].

IV. DATA ACQUISITION AND PROCESSING

A. *Geotechnical investigation*

The borehole was drilled down to 30.45 m. Standard Penetration Test (SPT) was carried out in the upper 8.25 m with a split-barrel sampler with 63.5 kg hammer dropped 0.76 m, until refusal according to [24].

At the laboratory the samples were tested according to the American Society for Testing and Materials (ASTM) regulations. Some properties that were determined were:

- water content [25]
- Soil classification [26]
- Specific gravity [27]
- Direct Shear Test of Soils Under Consolidated Drained Conditions [28]
- Unconfined Compressive Strength of Intact RockCore Specimens [29]

B. *HVSR Methodology*

The Nakamura analysis was done twice, one with microtremors and the other with seismic tremors.

B.1 Analysis of microtremors:

A GEOtiny triaxial seismograph was placed inside the building of the accelerograph station (Fig. 5) to avoid interferences from the wind, human footprints and any other object movement that could distort the record. The sample was recorded in dynamic 100 Hz range and RMS 129 Db for 45 minutes.

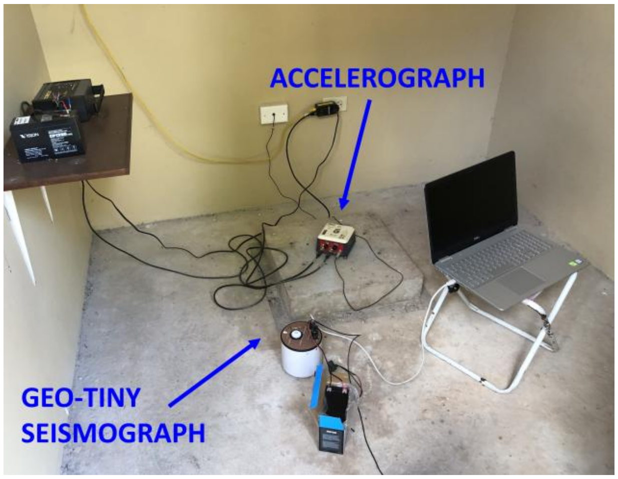

Fig. 5 Accelerograph station

The data processing was done with the Geopsy software. The frequencies were band pass filtered in a range from 0.05 Hz to 20 Hz. Also, the signals were aligned with the zero axis by using a Tucky window at 25%. Later, the signal windows that had irregularities were unselected to avoid using signals that does not correspond to microtremors (Fig. 6).

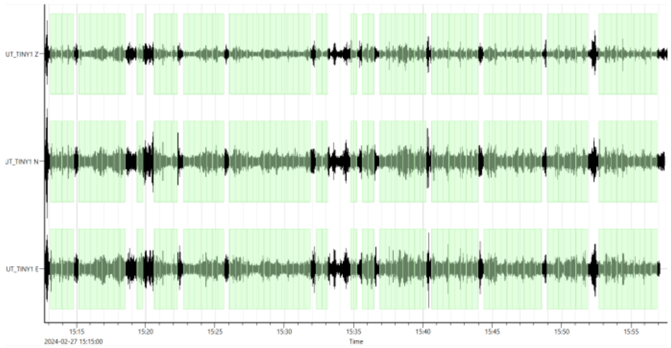

Fig. 6 Windows used for processing.

Once the average spectrum is calculated, it was verified that spectral density graph in the fundamental vibration frequency had eye-shaped behaviour. This proves that the processing is well done.

B.2 Seismic tremor analysis:

The processing was realized by choosing 3 seismic time histories from the data base of the campus accelerograph station. In this case there is no need to delete data from the signals because they all correspond to the natural event. However, as before, it was verified that the spectral density graph had eye-shaped behaviour.

C. Refraction of Microtremors (ReMi) methodology

An alignment of 69 m was made with a measuring tape near the accelerograph station. This distance (L) was chosen to try to achieve a maximum investigation depth (D) over 30 m [19].

$$\frac{L}{3} < D < \frac{L}{2} \quad (7)$$

To cover this distance, 24 vertical 4.5 Hz geophones were used, in an interval of 3 m, and connected through two multicables systems to a GEA24 seismograph (Fig. 7).

Fig. 7 ReMi test carried out in the area of study.

Before starting to record, it was verified that all the geophones were correctly placed and that they had a well connection between the cables and the seismograph. Later, the record was setup in passive sampling mode from 2ms-500 Hz with a lag time of 0 seconds, an acquisition time of 32 s with a 1 s interval and 20 repetitions.

The collected data was processed with the WinMASW software professional version. The data was selected, and the software was setup in ReMi and re-sampled in a range of 2 ms to 7 ms in a sampling of 8 ms.

In addition, the limits of the spectral and wave phase velocity must be introduced. As in this study those parameters are not known, they are established by rough estimations.

Afterwards, the program shows graphs of spectral wave velocities of each file. The average is used for the picking process. From this graph the points that correspond to the energy amount of the Rayleigh wave are selected.

It is important to note that due to the rough estimations that are made, the whole process is repeated as necessary. The final shear wave velocity profile is selected when the model gives a great match of the mean and the fittest model.

D. Correlation equations

The shear wave velocity is estimated for the upper 8.25 m with the PEER guideline and the rest of the depth with the corresponding correlations for rocks.

The shear-wave velocity was calculated for each depth where data was reported from the borehole geotechnical investigation. Then the estimated profile was computed by assigning the calculated Vs of each depth to half the upper and down separation between depths.

Afterwards, the equation proposed by [10] for average shear wave velocity was used to estimate the shear wave velocity for the upper 30 m.

$$\overline{V_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \quad (8)$$

Where d corresponds to depth of each layer and V_{si} the shear wave velocity at each depth.

Taking as a basis, the V_s from the ReMi method at each depth, the Least Square Method was implemented for all the combinations of equations. This statistic method states that the minimum value of the sum of the quadratic difference between the observed and calculated data, gives the best fit to the ideal equation [30].

According to the LSM the 3 best fit equations were selected as the ones that best fit the shear-wave velocity profile estimated with ReMi.

On the other hand, when the properties have been estimated by correlations, (9) for the fundamental period of the site proposed by [18] is implemented. In order to estimate the site classification according to equations.

$$T_G = 4\sum_{i=1}^{n}\frac{H_i}{V_{Si}} \quad (9)$$

Where H_i corresponds to the thickness and V_{Si} to the shear wave velocity of each layer.

V. RESULTS

A. Geotechnical investigation

The site has four layers: 3m of fat clay, 5.25m of lean clay with sand, 8.4m of moderately weathered limestone and the rest correspond to bedrock.The uncorrected blow counts for the clay layers are shown at Table IV. While the rock properties used in this study are shown on Table V.

TABLE IV
STANDARD PENETRATION TEST, SPT

Depth (m)	Uncorrected blow counts (N_{SPT})
1.45	7
2.45	7
3.45	10
4.45	9
5.45	36
6.45	27
7.45	55
8.25	100

TABLE V
UNCONFINED COMPRESSIVE STRENGTH ROCK CORE SPECIMENS

Depth (m)	q_u (Mpa)	ρ_m (kN/m^3)
12.35	28.3	23.42
15.35	30.4	23.66
18.00	52.1	26.45
18.55	30.1	26.05
19.75	25.1	23.09
21.05	30.8	24.76
22.65	16.4	22.99
23.75	33.5	25.57
25.25	17.5	23.75
26.75	1.0	26.73
28.35	22.2	24.36
30.20	28.0	24.82

B. HVSR Methodology

The microtremor analysis Fig. 8 showed that the fundamental frequency of the site corresponds to 6.37 Hz.

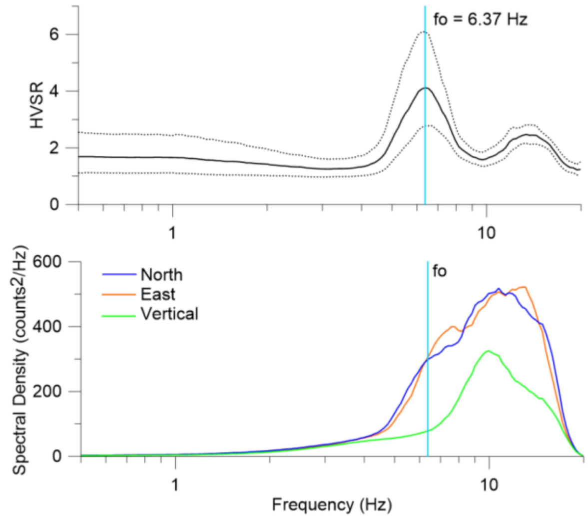

Fig. 8 HVSR spectra for microtremors analysis.

On the other hand, the seismic tremor analysis showed in Fig.9 that the fundamental frequency of the site is 6.03 Hz, 5.77 Hz and 6.22 Hz, for the first, second and third seismic record consequently.

C. Refraction of Microtremors methodology

This analysis represented a shear wave velocity one dimensional profile of 3 layers. Where the first layer has a Vs of 305 m/s, the second layer 138 m/s and the last layer 697 m/s. (Fig. 10)

Also, an average shear wave velocity for the upper 30m is determined as 386 m/s.

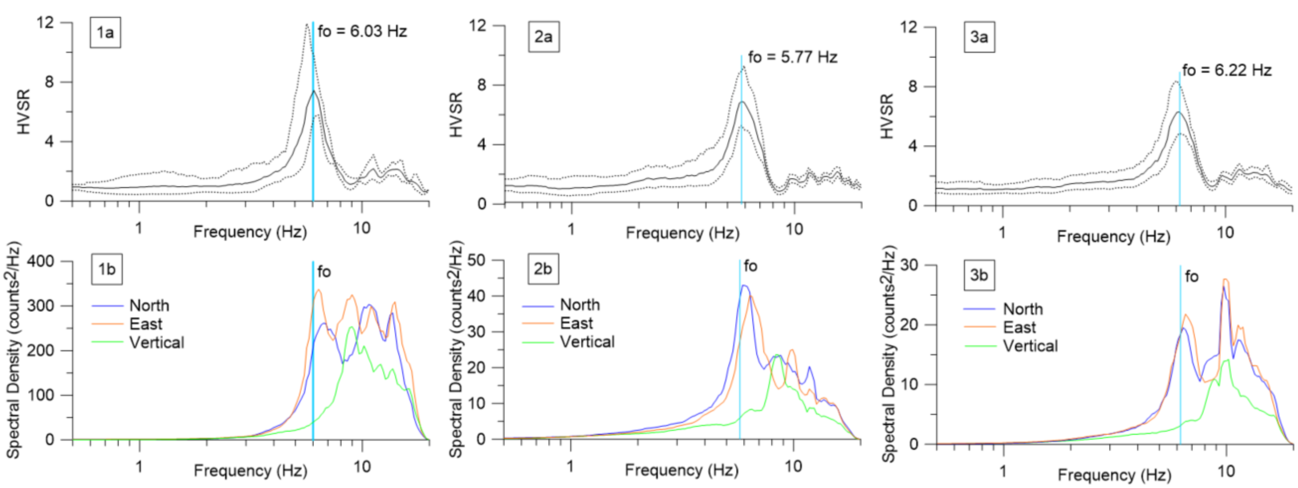

Fig. 9 HVSR spectra for seismic tremors analysis.

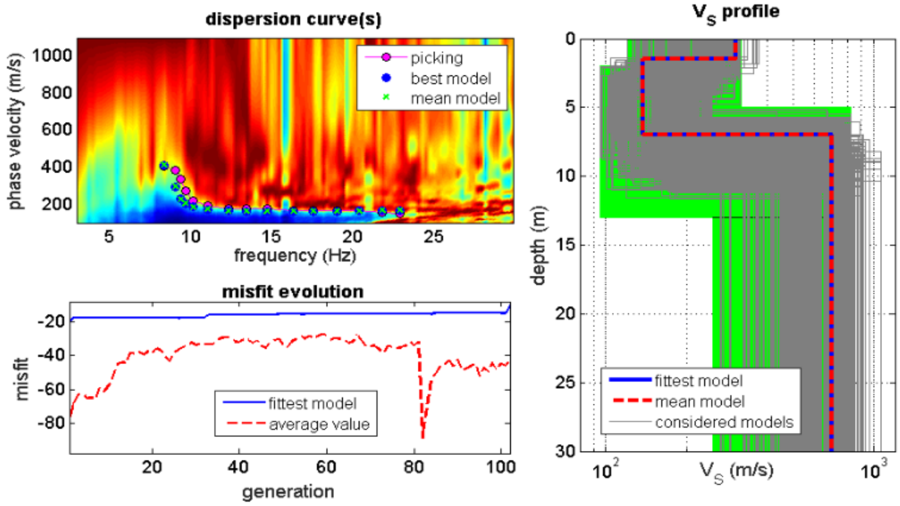

Fig. 10 ReMi test results.

D. *Correlation equations*

The average shear-wave velocity for the upper 30 m estimation considering the different correlations for the clay layers are shown in the table below. As well as the percentual error of each calculation taking as a basis the result obtained from the ReMi method.

Because (2.21) used for the first two layers, in combination with the equation for rocks, gives the least square, it is used for the rest of the calculations needed to estimate the site classification (Table VI).

TABLE VI
LEAST SQUARE METHOD, V_{S30} AND PERCENTUAL ERROR CALCULATIED FOR EACH CORRELATION

Equation	Least Square Method	$V_{s(30)}$	|E| %
(2.1)	427,837.24	393.39	1.91
(2.2)	324,854.30	434.39	12.54
(2.3)	363,963.99	419.35	8.64
(2.4)	466,682.94	384.94	0.28
(2.5)	364,528.62	471.31	22.10
(2.6)	382,916.08	422.79	9.53
(2.7)	344,260.18	456.39	18.24
(2.8)	280,085.39	453.99	17.61
(2.9)	480,293.95	305.89	20.75
(2.10)	286,269.59	410.46	6.34
(2.11)	459,131.20	407.68	5.62
(2.12)	560,384.37	331.69	14.07
(2.13)	407,782.74	405.60	5.08
(2.14)	377,669.63	413.66	7.17
(2.15)	498,208.56	374.05	3.10
(2.16)	381,924.65	458.83	18.87
(2.17)	475,699.51	386.49	0.13
(2.18)	412,150.19	418.86	8.51
(2.19)	379,756.97	453.58	17.51
(3.1)	390,870.54	462.33	19.77
(2.20)	365,847.94	467.47	21.11
(2.21)	262,657.92	386.92	0.24
(2.22)	443,292.15	398.52	3.24
(4.1)	497,128.35	391.67	1.47
(4.2)	380,340.46	460.69	19.35

VI. DISCUSSION

A. *Fundamental frequency estimation*

Taking as a basis, the fundamental frequency obtained from the HVSR of seismic tremors, an error of 5.81% is obtained when using micro tremor. While a considerable error of 46.44% is obtained when using estimated equations. (Table VII)

B. *Shear wave velocity*

Comparison between all correlations (i.e. Table III) and results from ReMi analyses are shown in the appendix to this paper. In Fig. 11 it can be observed that the combination of (2.21), (2.8), (2.10) for clays and (5) for rocks fits the best in reference to the ideal shear-wave velocity profile estimated with ReMi.

Also, according to the average shear wave velocity in the upper 30 m in table VI, it has only a percentual error of 0.24%, 17.61% and 6.34% respectively.

C. *Site classification*

The site classification according to the two geophysical methods are consistent with each other. However, the site classification from estimated values, indicates a different type of soil.

TABLE VII
COMPARISON OF FUNDAMENTAL FREQUENCY

Method	f0 (Hz)	|E|%
Nakamura: Seismic data	6.02	-
Nakamura: environmental noise	6.37	5.81
Estimated	3.22	46.44

TABLE VIII
COMPARISON OF SOIL TYPE ACCORDING TO THE METHODOLOGY

Based methodology	Type of soil
ReMi	C: hard and/or very stiff soil
HVSR	SC I: rock/stiff soil
Estimated with f0	SC II: rigid soil

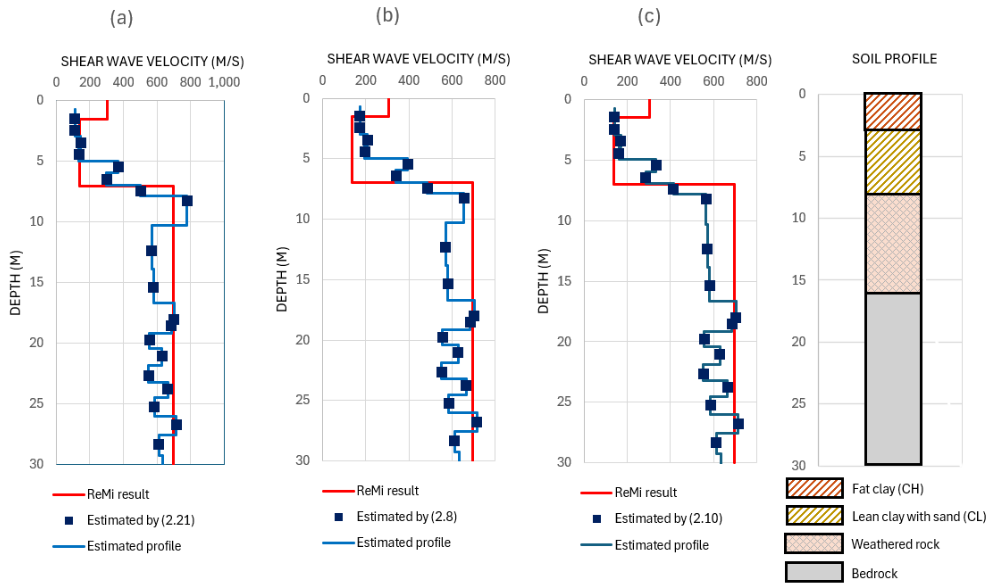

Fig. 11 Shear wave velocities profiles comparison with the soil profile.

VII. CONCLUSIONS

The HVSR method with micro tremors accurately represents the fundamental vibration frequency of the site in reference to the seismic tremor analysis. The fundamental vibration frequency estimated from the inverse of (9) does not represent accurately the soil property. These facts reflect the need to develop more research on the prediction of fundamental soil periods based on SPT (or similar data) for the case of residual soils.

Even though the Vs profile could not be compared with in situ destructive tests, the comparison with the soil profile demonstrated that the profile correctly reflects the occurrence of different soil layers.

Panama´s soil is mainly residual, and there are no correlations in this kind of soils, which results on inadequately use of equations from other countries in our location. Thus, correlations to obtain de Vs of a layer of soil cannot be used lightly. This is due to the fact that equations are calibrated to specific site conditions. If correlations for determining Vs of a layer of soil were wanted, there is the need to do more site investigations in order to calibrate the equations to Panama´s.

This research reveals that, for rock Vs correlations, the estimations are majorly done by stress or primary wave velocity. As for clay, our kind of rocks are not the same as the ones used to calibrate equations in the majority of countries. Which will also result in overestimation of the Vs.

The combination of (2.21), (2.8), (2.10) for clays and (5) for rocks, resulted to be the most convenient equations for the estimation of Vs at the site of study. However, more research at different sites is required to establish a proper guideline on which equations are adequate.

The comparison between the results of the HVSR, ReMi and the soil profile demonstrated that the mentioned method correctly indicates the site classification.

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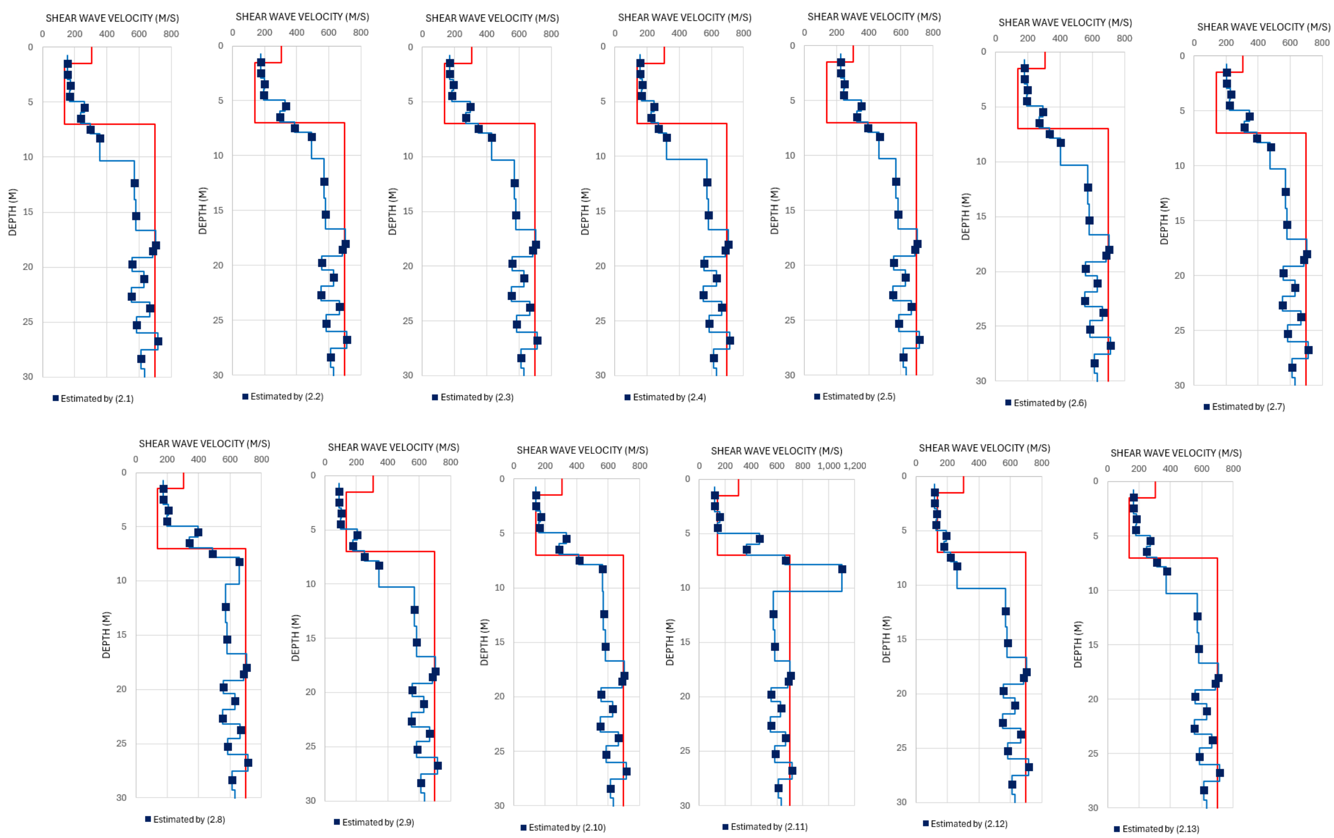
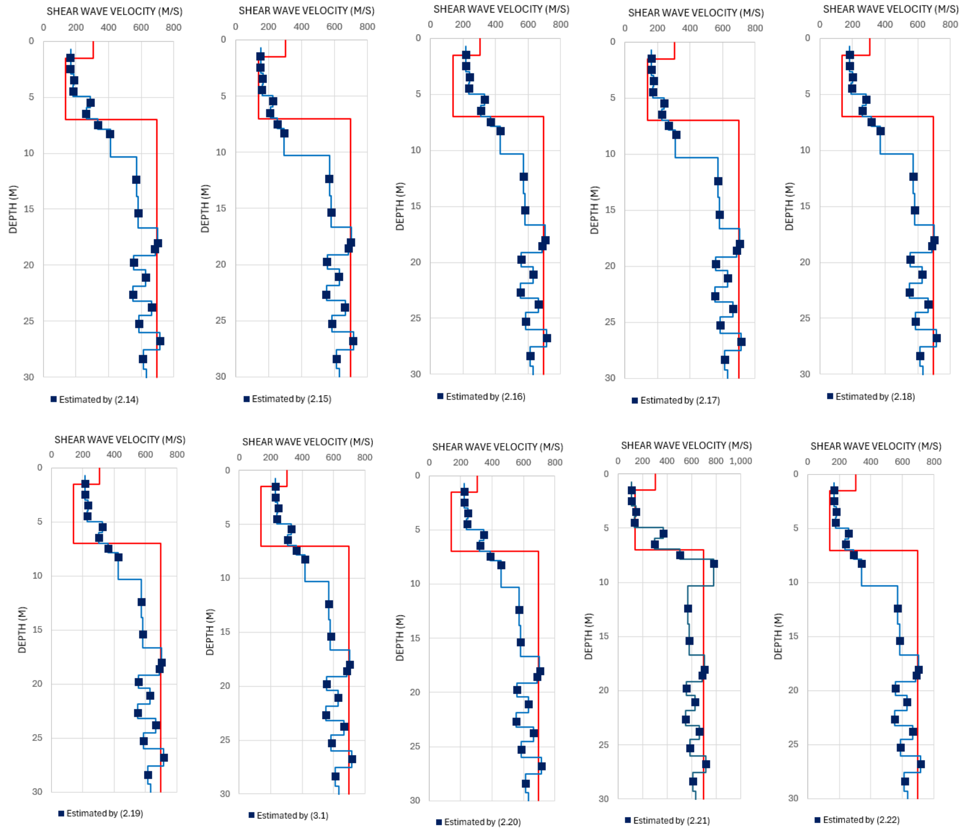
APPENDIX

Profile estimations with the correlations for all soils



Profile estimations with the correlations for clays



Profile estimations with the correlations for silts and clays