Research Article

Ambient Noise $H/V$ Spectral Ratio in Site Effect Estimation in La Mesa de Macaracas, Panama

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In the last 10 years, the community of La Mesa de Macaracas (central Panama) has experienced considerable aftershocks due to earthquakes of magnitudes up to 5.7 Mw. Although most of the community consists of single-storey houses, the agricultural development in the region has led to multistory building projects. To determine whether the characteristics of the soils could affect future construction in the study area, 16 stations were established to measure ambient vibrations and estimate the predominant frequencies and their corresponding $H/V$ ratio peaks through the ambient noise $H/V$ spectral ratio technique. According to the site class established by the Japan Road Association, the results revealed the existence of (a) soft soil with a range of predominant frequencies between 0.7 and 1.6 Hz, (b) medium soil with a range of predominant frequencies between 2.1 and 2.4 Hz, and (c) hard soil with a range of predominant frequencies between 2.6 and 2.9 Hz. In the first type (soft), the resonance effect could affect constructions of between 6 and 14 storeys with $H/V$ ratio peak values (amplification factor) in the range of 2.1 and 4.3, while in the second and third types (medium and hard soils), buildings of between 3 and 5 storeys could be affected, with $H/V$ ratio peak values (1.5–2.0) except at the SS-9 station. These results were complemented with the $V_s(30)$ values obtained in four seismic soundings carried out at the site.

1. Introduction

Mitigating seismic risk is a process closely related to site effect estimation, which can be performed by analyzing the vibrations generated by earthquakes, the impact of falling weights, or blasting [1]. However, this methodology can be time-consuming and costly, but the horizontal-to-vertical spectral analysis of ambient noise (or $H/V$ spectral ratio) can be the key to understanding the seismic site effects in urban and semirural or rural environments. Ambient noise also known as microtremors, refers to low-amplitude and short-period vibrations as an effect of the coasts, atmospheric loads, and wind interactions with structures and vegetation, industrial machinery, and traffic, for example. Interest in the details related to the study of soil stiffness and the interaction between buildings and soil in the predominant frequency (seismic response) was initially expressed by Nogoshi and Igarashi [2], who made numerous contributions in the use of surface waves, based on the study of the transfer function or $H/V$ spectral ratio. Subsequently, Nakamura [3] defined a theoretical framework of the method that could calculate the basement depth and a
vulnerability index of the surface terrain to estimate the damage an earthquake can cause to structures. At the beginning of the last century, Omori [4] discovered the presence of vibrations caused not by earthquakes but due to natural or artificial sources with amplitudes varying between 0.1 and 1.0 microns; later, Kanai and Tanaka [5] applied this concept to determine the dynamic behavior of soil. Finally, Horike [6] postulated that the vertical component of these microtremors basically consists of Rayleigh waves. Currently, several studies demonstrate the feasibility of using this type of technique for the estimation of the site response. Panou et al. [1, 7–10] have applied this technique to study the seismic risk in various areas.

In our country, in recent years, numerous efforts have been made to develop studies in this area, which increase knowledge and contribute to decision-making on policies regarding risk and the type of buildings in a given area so that structures are prepared for earthquakes of considerable

<table>
<thead>
<tr>
<th>Site class</th>
<th>Site natural period (s)</th>
<th>Predominant frequency $f_0$ (Hz)</th>
<th>$V_{30}$ (m/s)</th>
<th>NEHRP class</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC I: rock/stiff soil</td>
<td>$T_G &lt; 0.2$</td>
<td>$f_0 &gt; 5$</td>
<td>$V_{30} &gt; 600$</td>
<td>A+B</td>
</tr>
<tr>
<td>SC II: hard soil</td>
<td>$0.2 \leq T_G &lt; 0.4$</td>
<td>$2.5 &lt; f_0 \leq 5$</td>
<td>$300 &lt; V_{30} \leq 600$</td>
<td>C</td>
</tr>
<tr>
<td>SC III: medium soil</td>
<td>$0.4 \leq T_G &lt; 0.6$</td>
<td>$1.6 &lt; f_0 \leq 2.5$</td>
<td>$200 &lt; V_{30} \leq 300$</td>
<td>D</td>
</tr>
<tr>
<td>SC IV: soft soil</td>
<td>$T_G \geq 0.6$</td>
<td>$f_0 \leq 1.6$</td>
<td>$V_{30} \leq 200$</td>
<td>E</td>
</tr>
</tbody>
</table>

Table 1: Site class definition used in this project [16, 17] and the approximately corresponding NEHRP site class [18].
magnitude. For example, Echeverría [11] used the Nakamura technique to microzone the city of Puerto Armuelles. Furthermore, studies such as those conducted by Toral et al. [12–15] apply this technique to the study of seismic hazards and risks in Panama.

This research arises from the need to improve the scientific and technical knowledge base regarding the risk to buildings in the soils of our country and aims to study and determine the soil class according to the site class definition [16, 17] and the approximately corresponding NEHRP site class (see Table 1) and to estimate the potential risk to future buildings built in the region of La Mesa de Macaracas, Los Santos Province, using the ambient noise $H/V$ spectral ratio method.

2. Geological and Seismic Context of the Area

La Mesa de Macaracas is located in the center of the Azuero Peninsula, Los Santos Province, in the central region of the Isthmus of Panama (see Figure 1). The geological conditions are strongly influenced by the tectonic processes that produced the emergence and consolidation of the Isthmus of Panama. Therefore, in this sector we note a variety of effusive, fragmentary, and intrusive rock products of complex movements and differential displacements originating from the oceanic crust of Nazca and Coco, in addition to the orogenic processes evolving since the beginning of the Cretaceous.

The study area and surroundings are characterized by the geological formations shown in Figure 1. According to the Geological Map of Panama, igneous and sedimentary rocks emerged in the investigated area, whose formation ages comprise a wide time interval (83.6 to 13.8 Myr) [19]. The study area (La Mesa de Macaracas) is located on the Macaracas Formation, which is composed of tuffs and tuffaceous sandstones.

These general conditions of the site are affected by local faults, which have deformed the surface and left traces that are currently evident in the topography and in a large part of the main and secondary surface riverbeds. Therefore, geological-tectonic events during the Eocene and Early Oligocene gave way to volcanic processes that consolidated the aforementioned formations during the Late Oligocene. Epeirogenic processes affected the La Villa River basin, as well as the regional morphology and elevations of the area. The surface at the La Mesa de Macaracas site presents a high degree of weathering and components of sandy clays that retain the surface moisture of water in the vadose zone given...
the poor compaction of these sediments. The PEE-3 borehole well shown in Figure 2 reveals an unconsolidated stratigraphic sedimentary sequence. Within its components, granular fractions and fragments of silicified and mineralized rocks predominate. These subrounded fragments in combination with sandy and clayey material suggest the existence of a paleochannel, as these types of sub-rounded fragmentary rocks and their levels of hydrothermal alteration coincide with eroded mineralized outcrops located in the upper channels of the La Villa River, which were possibly washed away during epeirogenic processes in the Late Oligocene. Some 1D and 2D geophysical studies developed at the site corroborate the existence of this type of geological structure [20].

The area of La Mesa de Macaracas is seismically active and consists of various geological faults and would also be on the subduction interface plane between the Nazca plate and the Panama microplate. According to Bunduschuh and Alvarado [21] in Azuero, a system of active left-lateral strike-slip faults run in an NW-SE direction [22–24]. One of the most significant events close to the site was that on June 13, 2018, with a magnitude (Mw) of 5.2 and a dextral focal mechanism with an approximate east-west orientation, which is the characteristic of that region (see the focal mechanism of Figure 2).

3. \( V_s(30) \) Classification

At the study site, four seismic soundings (ReMi-1, 2, 3, and 4) were previously developed using the refraction microtremor method (ReMi survey) or multichannel analysis of surface waves [25], which permit the estimation of the S-wave velocity of subsoil through the study of surface waves. These soundings were separated by a distance of 117.5 m in a southwest–northeast direction (see Figure 3), where the average shear wave velocity for the top 30 m of soil (\( V_s(30) \)) values was obtained. These values were used to complement the results obtained in the ambient noise \( H/V \) spectral ratio in the site. For each sounding, 20 natural noise files were recorded using 16 low-frequency geophones with a geophone spacing of 10 m. For the generation of the dispersion images, the extraction of dispersion curves, and the inversion process, the ParkSEIS software was used. The results are shown in Figure 3.

The \( V_s(30) \) values, the dispersion curve match, and the depth of investigation (DOI) are summarized in Table 2.

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**Table 2: Dynamic soil parameters and match values between the observations and model response obtained from the inversion process for each seismic sounding.**

<table>
<thead>
<tr>
<th>Sounding</th>
<th>( V_s(30) ) m/s</th>
<th>DOI (m)</th>
<th>Dispersion curve match (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReMi-1</td>
<td>226</td>
<td>32.6</td>
<td>97.8</td>
</tr>
<tr>
<td>ReMi-2</td>
<td>261</td>
<td>69.6</td>
<td>94.1</td>
</tr>
<tr>
<td>ReMi-3</td>
<td>290</td>
<td>43.6</td>
<td>93.4</td>
</tr>
<tr>
<td>ReMi-4</td>
<td>301</td>
<td>60.8</td>
<td>94.5</td>
</tr>
</tbody>
</table>

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**Figure 3:** Stacked dispersion images and curves obtained for ReMi-1, 2, 3, and 4 sounding (a, b, c, and d, respectively) and 1D inversion results obtained for each dispersion curve of ReMi-1, 2, 3, and 4 soundings (e, f, g, and h, respectively). The yellow circles correspond to observations, the continuous red line is the model response, and the red dashed lines in 1D models are the DOI (depth of investigation).
4. H/V Spectral Ratio Technique

The H/V spectral ratio technique, also known as the Nakamura method, is based on a few assumptions, including the hypotheses that the energy of a microtremor consists mainly of Rayleigh-type surface waves and that the amplification effect of the site is due to the presence of a layer of soil on the surface that rests on a rocky mantle. Under these conditions, the amplitude spectra of four motion components are considered: two horizontal motion components recorded on the surface $H_s(f)$ and in the rock $H_b(f)$, and two vertical motion components recorded on the surface $V_s(f)$ and in the rock $V_b(f)$. From this, two important parameters can be defined: the first is related to the amplitude effect of the source through the $V_s(f)/V_b(f)$ ratio, and the second is linked to the site effects through the $H_s(f)/H_b(f)$ ratio [3]. From these, a modified site effect function $S_{M}(f)$ is defined to compensate for the effect of the source. The ratio between the site effects and the amplitude effect of the source represents this function. If it is assumed that the horizontal and vertical movements in the rock are equal, then the ratio $H_b(f)/V_b(f) = 1$, and the modified function is expressed as follows:

$$S_{M}(f) = \frac{H_s(f)}{V_s(f)}. \tag{1}$$

Equation (1) is also known as the Nakamura ratio.

5. Methodology

The present study was performed by collecting ambient noise data from 16 stations distributed in La Mesa de Macaracas (see Figure 4); these measurements were performed on December 10 and 11, 2020, which correspond to the beginning of the dry season in the Panamanian tropics where weather conditions are suitable. A portable seismograph GEOtiny (from GEObit) was used in which the sampling frequency was established at 100 Hz in a wide dynamic range with a root mean square (RMS) of 129 dB. At each station, the seismograph was aligned to the north and covered with a box to prevent wind effects. The recorded data were displayed on a laptop using SeisGram2K software and stored on the seismograph; a record length of 20 minutes was established at each station, noting the very low anthropic activity and its possible negative influence on the H/V ratio peaks; therefore, the measurements can be considered stratigraphic.

Ambient noise records were processed using the winMASW software (of Eliosoft) in two main steps. (1) The transient events present in the raw data of each channel were removed (i.e., raw data obtained in station SS-10, Figure 5(a)) through rectangles or windows that highlight them. A baseline correction is performed, and the data of the three components are displayed in the same graph as shown in Figure 5(b). (2) The three fundamental parameters were defined: window length, spectral smoothing, and tapering [26]. Moving this window (which can be a function of frequencies associated with H/V ratio peak values of interest) allows the H/V spectral ratio to be
computed for all considered windows or segments. The spectral smoothing can be relevant for the predominance of lower frequencies, and the tapering parameter is fixed to avoid artifacts during the computation of Fourier spectra [26]. Figures 5(c) and 5(d) illustrate the average of all computed $H/V$ spectral ratio curves and the standard deviations, and the average spectra for each component, respectively. These operations are based on the SESAME criteria [27].

In Figure 5(c), the predominant frequency obtained from the $H/V$ ratio peak curve coincides with the eye-shaped detachment in the average spectral curves of Figure 5(d), which means that the peaks are stratigraphic and not anthropic or artificial. These sources mainly affect the vertical component of the movement and therefore tend to induce Rayleigh waves [3].

6. Results

The Resulting Dataset Is Characterized by the Position ($x, y$) of Each Station (in UTM Coordinates) and the Predominant
Frequency (in Hz) Obtained from the H/V Ratio Peak (See Table 3).

### 6.1. Classification of H/V Spectral Ratios

Noting the shape of the graphs of the H/V spectral ratio versus the frequency and the H/V ratio peaks recorded in Table 3, two classes of spectral ratios are defined:

(i) **Class I**: spectral ratios with a moderately marked peak and H/V ratio peaks that vary between 1.5 and 2.0.

(ii) **Class II**: spectral ratios with a well-marked peak and H/V ratio peaks between 2.1 and 4.3.

This type of classification of H/V spectral ratios was proposed by Pastén [28]. Figure 6 presents two examples of the maximum frequency pulses obtained at stations SS-1 and SS-10.

### 6.2. Spatial Distribution of the Predominant Frequencies and H/V Ratio Peaks

The spatial distributions of the predominant frequencies and H/V ratio peaks were obtained using Surfer 19 software (Golden Software); these datasets were interpolated through kriging as an accurate gridding method, which is adapted in this software. Figure 7(a) shows the interpolated map of the predominant frequencies of the soils in the study site with the site classes defined in Table 1 (see predominant frequency limits in the color bar of this map).

Based on the classification of the H/V spectral ratios established at the previous point, a second interpolated map of H/V ratio peaks was developed (see Figure 7(b)). Figure 7(c) shows the spatial distribution of the georeferenced stations whose soils correspond to classes I and II.

### 7. Discussion

In the map in Figure 7(a), it is possible to identify the following zones:

(i) **The first zone** is represented by tuft blue and pale golden tones and characterized by the lower range of predominant frequency values (0.7 to 1.6 Hz). According to the literature, this range suggests soft soils in the eastern, western, and southwestern ends of the study area.

(ii) **The second zone** is located in the north-central part of the site and represented by flavescent and brick red tones. The range of predominant frequency values of this zone oscillates between 2.1 and 2.9 Hz; this range suggests medium and hard soil.

In the first zone is a seismic survey (ReMi-1) with a low value of $V_s(30)$ (226 m/s); this value can be associated with the transition zone between the soft and medium soils. In the second zone are the following three seismic surveys (ReMi-2, 3, and 4), with $V_s(30)$ values of 261, 290, and 301 m/s in which the first two are associated with medium soil and the last sounding with hard soil. These are complemented by the results of the predominant frequencies obtained in this study for the site classification.

The predominant frequency and the $V_s(30)$ values obtained show an increase towards the central north of the site. This could be associated with the fact that the soils are more consolidated in this area compared to the surroundings, according to the PEE-3 borehole and others carried out near of the site.

In the maps of Figures 7(b) and 7(c), two zones can be identified, which according to the ranges of the H/V ratio peaks (classification established by spectral ratio) are as follows:

(i) **The class I zone** is represented by green tones with a range of the H/V ratio peaks between 1.5 and 2.0. This zone is located in the north-central sector of the study area.

(ii) **The class II zone** is represented by yellow and orange tones with a range of H/V ratio peaks between 2.1 and 4.3. This zone occupies a large part of the study area, extending to the eastern, western, and southwestern ends of the site.

The spatial distributions of the predominant frequency and the H/V ratio peak values represented in the maps of Figure 7 appear to be partially related, as the zone of low predominant frequencies of the soil appears to be associated with the class II zone which presents high H/V ratio peak values (amplification effect), and according to Bodare [29], from the structural perspective of buildings and based on these field results, we can empirically establish that this zone would shake most strongly the constructions ranging between 6 and 14 storeys. This zone can be classified as soft soils. The north-central zone characterized by a higher range...
Figure 6: Examples of the $H/V$ spectral ratio classes obtained at stations SS-1 (class I) located in the northern area and SS-10 (class II) located in the central sector of the study area.

Figure 7: Interpolated maps that represent (a) the predominant frequencies of the soil, (b) the $H/V$ ratio peaks, and (c) the classification of the soils according to these $H/V$ ratio peaks.
of predominant frequencies seems to be associated with the class I zone, which has lower H/V ratio peak values, which agrees with medium and hard soils and could affect buildings with between 3 and 5 storeys.

There is an exception at the SS-9 station at the southwest end of the study area, where the predominant frequency suggests the existence of medium soil, but the H/V ratio peak value is associated with soft soil (class II zone). This exception could be associated with the size and distribution of the pebbles identified in the surface layer of the site through a borehole established in the southern part.

8. Conclusions

The validity of the estimation of the seismic response characteristic of the ambient noise measurements was investigated in La Mesa de Macaracas, Province of Los Santos, central sector of the Isthmus of Panama. The spatial distributions of predominant frequencies and the H/V ratio peaks of the soils suggest the existence of soft, medium, and hard soils in the study area. The range of predominant frequency obtained in this study (0.7–2.9 Hz) could be associated with a set of unconsolidated sedimentary sequences formed by subrounded alluvial fragments, sandy material, and clays with a thickness that could exceed 50 m. Two zones were clearly identified: the class I zone, with higher predominant frequency values (medium and hard soils) and lower spectral ratio values (low amplification), and the class II zone, characterized by a lower predominant frequency range (soft soil) and higher spectral ratio values (high amplification). Therefore, resonance could affect constructions that comprise 3 to 5 storeys in medium and hard soils and between 6 and 14 storeys in soft soils. For this type of geological environment, it is important to consider these results, noting the construction materials and minimum requirements established in the current structural regulations, thus ensuring that these civil works are not affected by significant seismic events. The classification developed in this work can be considered very useful for the structural analysis of new construction, since buildings or structures built on soft, medium, or hard soils could be affected by seismic amplification.

Data Availability

The data that supports this research is in the private database of the Centro Experimental de Ingeniería of the Universidad Tecnológica de Panamá, where special permits are required by the corresponding university authorities (contact by mail: alexis.mojica@utp.ac.pa).

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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