# COMPARISON OF SITE FUNDAMENTAL PERIOD ESTIMATES USING WEAK-MOTION EARTHQUAKES AND MICROTREMORS

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**ABSTRACT :**

This paper presents a comparison of the site period estimated with different techniques which use weak motion measurements recorded at seismic stations in Mayagüez, Puerto Rico. The stations are located in sites with soil profiles ranging from NEHRP classes B to E. The literature reports different degrees of success when estimating site periods based on low-intensity earthquakes and microtremor measurements. Some of the issues reported are related to effects due to differences in the seismic source, travel path, etc. This paper compares the dominant site periods computed using three well known methods, namely the Fourier amplitude spectra, the Fourier spectral ratios between the spectra at the site and at a reference station, and the spectral ratios between the horizontal and the vertical components of ambient vibrations (i.e., the Nakamura's technique). The paper also presents site period estimates based on two new techniques. The first approach proposed by Montejo and Suarez (2006) consists in the application of the wavelet transform to strong motion accelerograms. This paper applies for the first time this new technique to weak-motion earthquakes. The other new approach, proposed by Cano (2008), is based on random vibration theory applied to ambient vibrations.
The paper evaluates the applicability of the different techniques for various site conditions and weak motion earthquakes with different amplitude and frequency content and ambient vibration signals recorded at strong motion stations located in Mayagüez, Puerto Rico. The results show that weak-motion measurements can be used to estimate the dominant period of sites with acceptable reliability.

**KEYWORDS:** H/V spectral ratios, microtremors, Nakamura technique, site periods, weak motions

## 1. INTRODUCTION

It is well documented that reliable seismic hazard analyses (SHA) require adequate consideration of the local site effects. Ideally a thorough SHA would require good knowledge of local geotechnical, topographic, and geologic conditions, assessment of soil and rock properties through laboratory and in-situ tests, etc. However, in practice SHA often only have availability to limited data for a given site. In recent years a popular approach to assess local site effects has been to use seismic instrumentation (geophones, seismographs or accelerographs) to monitor either microtremors (a term used herein as equivalent to ambient seismic noise or low amplitude vibrations) or weak-motion earthquakes at the site of interest (e.g., SESAME, 2004). This approach has been particularly useful for areas with low seismic recurrence where data of strong motion earthquakes is limited or not available. Such is the case for Puerto Rico, a Caribbean island that is considered to have high seismic potential but with no strong motion data available.

This paper focuses on the evaluation of the predominant site period using ambient vibrations and weak motion earthquakes. The paper does not attempt to estimate site amplification factors given that some researchers have indicated that weak earthquakes are not reliable for this purpose (e.g., Field et al., 1997 ) while others have reported they can be used for this purpose (e.g., Trifunac and Todorovska, 2000).

The paper applies different approaches for estimating predominant site periods for four sites in the city of Mayagüez located in the western part of the island of Puerto Rico, a US territory in the Caribbean. The estimates were based on application of well established methods, such as the Nakamura technique and the conventional Fourier spectral ratio, as well as application of two less common techniques: a wavelet-based approach suggested by Montejo and Suarez (2006) and an approach using a mean time-frequency representation that uses a reduced interference distribution proposed by Cano (2008). This paper compares the estimated dominant periods obtained by applying five techniques to recordings of weak motion earthquakes and ambient vibrations records measured at the strong-motion stations of the seismic network Puerto Rico Strong Motion Program (PRSMP). The four stations are located in sites with soil profiles ranging from a competent dense soil/weak rock site to soft sediment sites.

## 2. TECHNIQUES USED FOR ESTIMATING THE SITE DOMINANT PERIODS

The following subsections describe briefly the techniques used for analyzing the different kind of data to determine the dominant periods of several sites in Mayagüez, Puerto Rico. More details can be found in the references listed in Table 1.

### *2.1 Direct Interpretation of the Fourier Transform Spectra (FTS)*

This technique consists of examining the computed Fourier spectrum for the horizontal component of the recorded data. This technique has been applied to both microtremors and earthquake records (e.g., Lermo and Chavez-Garcia, 1984; Ojeda and Escallon, 2000). Here the Fourier spectra of the horizontal components of the ambient vibration records are examined to determine the dominant frequencies. Interpretation of the dominant periods can be difficult for earthquake records where the dominant period of the ground motion is very different from the fundamental period of the site. This technique is only recommended for preliminary screening of the data until more research is done to assess its reliability.

### *2.2. Spectral Ratios with respect to a Reference Site (SRRS)*

This method is sometimes referred to as Kagami's ratio and as the Borcherdt's method by other authors. Kagami et al. (1982) used the approach with micro-tremors and Borcherdt (1970) applied this technique to ground motions recorded in several stations in the San Francisco Bay area generated by nuclear explosions in Nevada. The latter author also analyzed strong-motion data from the San Francisco earthquake of March 22, 1957. The methodology consists of computing the ratio of the horizontal components of the Fourier spectral amplitudes of the motions recorded at a sediment site and a nearby reference rock site (related to a common source). The spectral ratio is computed as follows:

$$K_{SB} = \frac{H_S}{H_B} \tag{2.1}$$

where $H_S$ and $H_B$, are the horizontal Fourier spectral values of the sediment site and the bedrock reference site, respectively. In this paper the SRRS method was applied only to the weak motion earthquake recordings.

### *2.3. Horizontal-to-Vertical Spectral Ratios (HVSR)*

This method is attributed to Nakamura (1989) and in essence involves computing the spectral ratio between the horizontal and vertical components of the recordings at the site of interest. No bedrock site of reference is required for application of this technique. A more detailed description of the Nakamura technique was provided by Nakamura (2000). The literature shows that the technique has been used primarily with microtremors recordings but it has also been applied to earthquake records. The methodology applied to microtremors was studied in considerable detail in the European research project SESAME (SESAME, 2004).

The procedure for processing the ambient vibration recordings requires several steps, such as: signal corrections, sampling window selections, signal filtering (e.g., Hanning window), computation of Fourier spectra of the three components, smoothing, computation of H/V ratios (see Eqn. 2.2 below), and calculation of mean and standard deviation of the H/V spectral ratios. This process has been automated in the software JSESAME (SESAME, 2004) but it can also be easily programmed. The results presented in this paper were analyzed using both the JSESAME software and an in-house program written in Matlab. The H/V ratio is usually defined as:

$$\frac{H}{V} = \sqrt{\frac{H_{E-W}^2 + H_{N-S}^2}{2 \cdot V^2}} \tag{2.2}$$

where $H_{E-W}$ and $H_{N-S}$ are, respectively, the horizontal spectral values in the E-W and N-S directions and V is the spectral value in the vertical direction. In this paper the HVSR method was applied to both ambient vibrations (abbreviated herein as HVSR-AV) and to weak motion earthquakes (abbreviated in this paper as HVSR-WM).

### *2.4. Wavelet-based analysis (WAVELET)*

This technique was proposed by Montejo and Suarez (2006) to estimate predominant periods of sites using strong motion records. The authors devised a wavelet-based procedure that can be applied to analyze historic earthquake accelerograms recorded at the surface of free-field sites. In this method the acceleration time histories are analyzed with the continuous wavelet transform, in particular with the complex Morlet wavelet. The procedure is based on a zoom-in of the wavelet map (a 2-D time-frequency representation of a signal) after the strong motion part of the earthquake fades away. Montejo and Suarez (2006) were able to identify reliably the first natural frequencies of several leveled ground sites and in a few occasions also the second frequency. This paper presents results of applying this technique for weak earthquake motions.

### *2.5. Mean Time-Frequency Representation Using Reduced Interference Distribution (MTFR-RID)*

This method uses time-frequency representations (TFR) of continuous recordings of ambient vibrations (preferably long records of several hours or days). A TFR represents a distribution of the energy in the signal as a function of time and frequency. Cano (2008) applies a reduced interference scheme to improve the resolution of the TFR. This scheme consists in eliminating frequency contents that are not relevant to the process. Cano (2008) applied the method to structural damage detection. This is the first attempt to apply this procedure for detection of site frequencies.

## 3. DESCRIPTION OF THE AREA OF THE RECORDING SITES

Ground motions were recorded and analyzed at four monitoring sites within the city of Mayagüez located in western shore of Puerto Rico (Fig. 1). The island of Puerto Rico (PR) is located in a very active and complex tectonic region in the northeastern Caribbean Sea. Most of the seismic activity of the area is produced by the convergence and lateral translation of the North American and Caribbean Plates beneath the Puerto Rico Platelet (Tuttle et al., 2003). Figure 1 shows the main seismic sources affecting Puerto Rico. The offshore active faults shown in Figure 1 are considered the major sources of seismic activity on the island. The main offshore seismic sources include the Mona Canyon (extension zone located to the west), the Anegada Passage (extension zones located to the east side of the island), the Puerto Rico Trench (subduction zone to the north side of PR), and the Muertos Trough (subduction zone to the south). Another set of seismic sources involve inland fault zones which include two fault zones that cross the island from northwest to southeast, namely the Great Southern Puerto Rico Fault Zone (labeled as GSPRFZ) and Great Northern Puerto Rico Fault Zone (GNPRFZ) and the South Lajas Fault (SLF), located in the south west corner recently identified by Prentice and Mann (2005).

For the area of study, i.e. the city of Mayagüez, the most important potential seismic sources are the Puerto Rico Trench, the Muertos Trough and the Mona Canyon (McCann, 1987). It has been estimated that the Puerto Rico Trench is capable of generating maximum events with a magnitude of about M ~ 8.0 (McCann, 1987). Also, according to McCann (1987) the Muertos Trough is considered to be capable of producing events of M ~7.5 to

8.0. However, the seismicity produced by the Mona Canyon or Passage is considered to be the most threatening for cities along the west coast of PR due to the proximity to the area. This zone is capable of generating shocks of M ~ 7.5 to 8.0 (McCann, 1987). In 1918, the Mona Passage generated the most damaging earthquake affecting the Mayagüez area with an estimated magnitude of 7.5. Approximately 116 people died due to this event and $4 million in property damage was estimated (Reid and Taber, 1919).

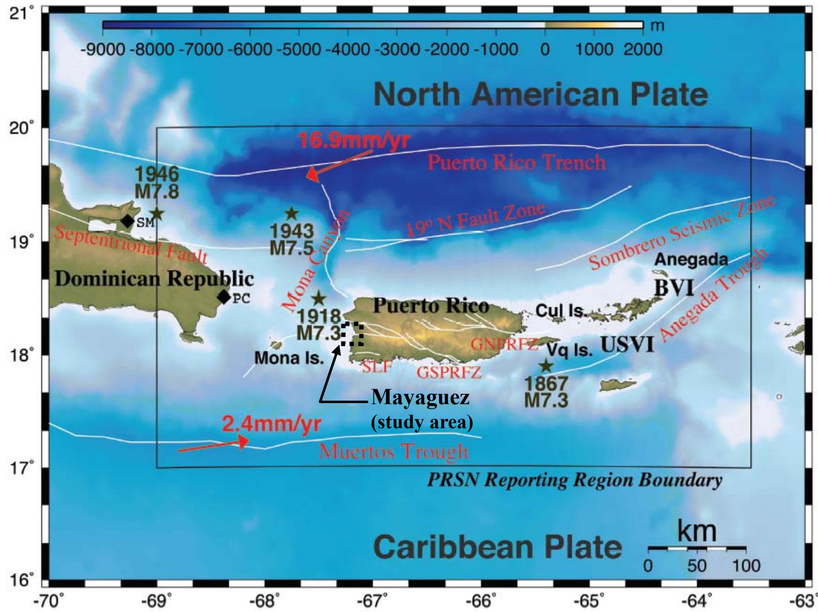



Figure 1 Seismic Settings of Puerto Rico (Adapted from Clinton et al., 2006)

Being a coastal city, the topography of Mayagüez is variable. Near the shoreline, i.e. west end of the city, the terrain is flat to mildly sloping. This relatively flat coastal area is comprised of beach and alluvial deposits of the Holocene age. Near the rivers (e.g., Guanajibo River) the soils are alluvial deposits from the Late Pleistocene and Holocene. They are described as poorly to moderately sorted, moderately to well-bedded sand, silt, and cobble or boulder gravel (Moya and McCann, 1992) and can have considerable thicknesses of the order of 120 ft or more. To the east and the northeast part of the city the terrain is mountainous. In the mountainous area, away from rivers and creeks, the surficial geology predominantly consists of residual soils which are usually more competent than the alluvial and beach deposits.

The general geology for the Mayagüez area has been mapped by Curet (1986). In general, the Mayagüez area lies between the contact of two different geologic units: the Sierra Bermeja Complex and a volcanic complex (Moya and McCann, 1992). These authors describe the Sierra Bermeja Complex as composed mainly by volcanic and metamorphic rocks of pre-Cretaceous to Early Cretaceous age and is considered as the oldest rock formation in the island. The volcanic complex is a folded sequence of sedimentary and volcanic rocks of Late Cretaceous to Early Tertiary age that overlays the Sierra Bermeja Complex (Moya and McCann, 1992). More details of the geology and geotechnical characteristics of the study area can be found in Pando et al. (2006).

## 4. INFORMATION OF THE SITES MONITORED

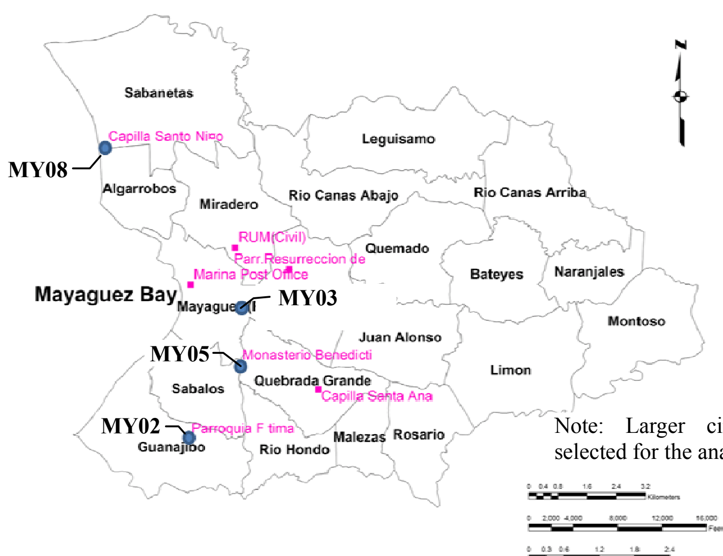
The ground motions analyzed in this paper were recorded at four strong motion stations in the city of Mayagüez. These stations form part of the relatively dense strong motion instrumentation network of the city which is administered by the Puerto Rico Strong Motion Program (PRSMP). Figure 2 shows the locations of the seismic stations currently monitoring in Mayagüez as well as the four stations analyzed. Table 1 summarizes relevant information regarding each of the stations studied in this paper.

Table 1 Information of strong motion sites analyzed

| Station Name | Abbrev. | Geographic Coordinates | Sensor Type | Trigger[1] Level (%g) | Ground conditions[2] |
|---|---|---|---|---|---|
| Fatima Parish | MY02 | N 18.167150<br>W 67.151370 | Triaxial EpiSensor | H = 1.0<br>V = 0.2 | NEHRP soil class: D<br>Topography: Leveled |
| Santo Niño de Praga Chapel | MY03 | N 18.240750<br>W 67.172200 | Triaxial EpiSensor | H = 1.0<br>V = 0.2 | NEHRP soil class: F<br>Topography: Leveled |
| Benedictine Monastery | MY05 | N 18.185450<br>W 67.138030 | Triaxial EpiSensor | H = 1.0<br>V = 0.2 | NEHRP soil class: B/C<br>Topography: Top of hill |
| Cathedral Parish House | MY08 | N 18.200178<br>W 67.137512 | Triaxial EpiSensor | H = 1.0<br>V = 0.2 | NEHRP soil class: E<br>Topography: Leveled |

Notes: (1): Trigger levels reported are the operational values used by the PRSMP. For ambient vibrations the trigger levels were removed to ensure continuous recording. H = horizontal components, V = vertical component. (2): NEHRP soil classification as per BSSC (2001). NEHRP site classes for the sites are based on Llavona (2004) and Pando et al. (2006).

Of the four sites listed above, MY05 was selected as the reference "rock" site for the SRRS methodology. This site is located in the Benedictine Monastery of Mayagüez and is considered the most competent site of the stations within the city. The soil profile for this site is considered to correspond to a NEHRP soil classification type between C and B which would correspond to a very dense soil to soft to medium rock with an average shear-wave velocity of the top 30 m between 360 and 760 m/s (1200 to 2500 ft/s). This site was also selected as reference because it is located on the top of a competent hill that falls within the Maricao geologic stratigraphic formation described as composed of massive breccia, conglomerate sandstone and limestone (Curet, 1986). Therefore all predominant period predictions requiring ratios with respect to a bedrock site of reference were computed using Station MY05 as the reference site.




Note: Larger circular symbols denote sites selected for the analyses presented in this article.

Figure 2 Free field strong motion stations in the city of Mayagüez, Puerto Rico

## 5. GROUND MOTIONS RECORDED

The ground motions analyzed included two weak earthquake events and ambient vibrations recorded continuously at each site for a period of 24 hours. The two seismic events analyzed were recorded on December 11, 2000 and on October 17, 2001. The December 2000 event had a magnitude $M_w$ of 5.4 and was generated by the Puerto Rico Trench zone (see Fig. 1) at an estimated depth of 46.9 km (PRSMP, 2008). The October 2001 event was estimated as having a local magnitude $M_L$ of 4.3 and was generated by the Mona Canyon (see Fig. 1) at an estimated depth of 25.1 km (PRSMP, 2008). The peak ground accelerations (PGA) for these two weak motion earthquakes are summarized in Table 2.

Table 2 Summary of PGA recordings for the two weak motion earthquakes

| Station | Estimated NEHRP Class | December 11, 2000 (Mw = 5.4) | | October 17, 2001 ($M_L$ = 4.3) | | Ambient vibrations |
|---|---|---|---|---|---|---|
| | | Horizontal PGA ($cm/s^2$) | Vertical PGA ($cm/s^2$) | Horizontal PGA ($cm/s^2$) | Vertical PGA ($cm/s^2$) | Horizontal PGA ($cm/s^2$) |
| MY02 | D | 5.59 | 1.88 | 6.09 | 2.82 | 0.016 |
| MY03 | F (E)[1] | 5.83 | 2.81 | 11.27 | 9.19 | 0.011 |
| MY05 | B/C | 2.23 | 1.21 | 5.72 | 2.27 | 0.006 |
| MY08 | E | 7.95 | 1.92 | 12.53 | 3.47 | 0.014 |

Note: (1) Site MY03 is listed as NEHRP Class F because of liquefaction susceptibility. In terms of shear wave velocity profile it classifies as Class E.

As expected, higher horizontal PGA values were recorded in stations MY03 and MY08 which have the lowest NEHRP class ratings. The PGA values for the October 2001 event were higher than the December 2000 event primarily due to the closer proximity of this event which originated in the Mona Passage.

Table 2 also shows the horizontal PGA for the ambient vibration measurements. These values highlight the different order of magnitude of the measurements and can also be used to estimate the signal to noise ratio for the earthquake records since noise due to ambient vibrations is present during these motions.

## 6. RESULTS

The estimated predominant site periods for the four recording sites are summarized in Table 3. The table presents results in two groups: estimates based on weak motion earthquake recordings and ambient vibrations (micro-tremors).

Table 3 Summary of Estimates of Predominant Site Periods and Frequencies (frequencies in parenthesis)

| Station | NEHRP Class | Estimates based on weak earthquakes | | | Estimates based on microtremors | | |
|---|---|---|---|---|---|---|---|
| | | SRRS | HVSR-WM | WAVELET | FTS-AV | HVSR-AV | MTFR-RID |
| MY02 | D | 0.21 s (4.78 Hz) | 0.31 s (3.21 Hz) | 0.21 s (4.75 Hz) | 0.21 s (4.87 Hz) | 0.18 s (5.57 Hz) | 0.20 s (5.03 Hz) |
| MY03 | F (E) | 0.56 s (1.77 Hz) | 0.52 s (1.94 Hz) | 0.63 s (1.60 Hz) | 0.37 s (2.70 Hz) | 0.39 s (2.55 Hz) | 0.45 s (2.2 Hz) |
| MY05 | B/C | Ref. | 0.19 s (5.32 Hz) | 0.13 s (8 Hz) | 0.10 s (10.0 Hz) | 0.10 s (9.7 Hz) | 0.19 s (5.4 Hz) |
| MY08 | E | 0.28 s (3.60 Hz) | 0.27 s (3.74 Hz) | 0.27 s (3.75 Hz) | 0.27 s (3.73 Hz) | 0.27 s (3.70 Hz) | 0.28 s (3.61 Hz) |

Notes: FTS = Direct interpretation of Fourier spectrum; SRRS = Spectral ratios with respect to a rock reference site (Kagami); HVSR = Horizontal-to-Vertical spectral ratios at a given site (Nakamura); WM = weak motions; AV = Ambient Vibration; WAVELET = wavelet-based method of Montejo and Suarez (2006); MTFR-RID = Method by Cano (2008); Ref.=reference site.

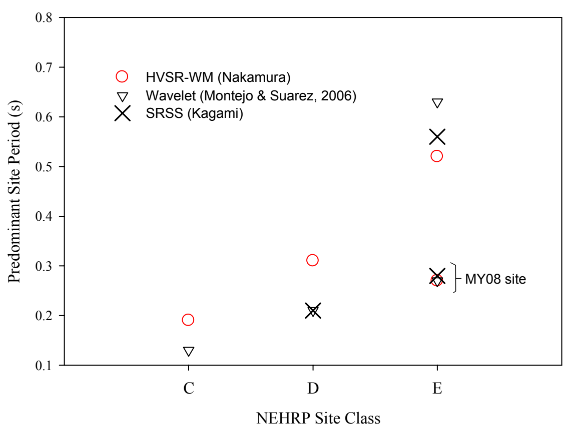
For the sake of brevity, Table 3 only lists predictions using the HVSR-AV method and the in-house (UPRM) Matlab program. However, these results compared well with predictions using the program JSESAME created as part of the European project SESAME mentioned earlier.

## 7. DISCUSSION OF RESULTS

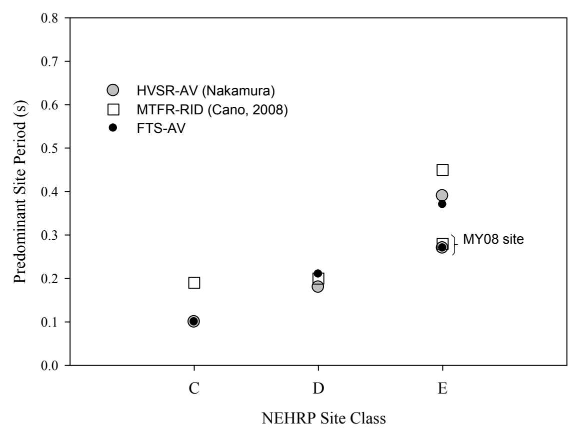
In general, the predictions obtained with the different methods compare reasonably well. The MTFRD-RID (Cano, 2008) yielded estimates that were the closest to the average values computed considering all methods. The HVSR-AV (i.e. Nakamura's method with ambient vibrations) was the method that provided estimates that departed the most from the average values computed considering all methods. The largest dispersion of results, based on computed coefficients of variations (CoV), was obtained for stations MY05 and MY02 with CoV values of 29 and 23%, respectively.

In terms of computation efforts, the simplest method to apply was the HVSR-AV which has the additional advantage that data can readily be obtained without the need of having to wait for earthquake motions.

Figures 3(a) and 3(b) show, respectively, comparisons of predominant period estimates, grouped in terms of NEHRP site class, for the methods that used weak motions and micro-tremors. The values predicted follow the trend expected, as the site periods increase with higher NEHRP site class (higher in terms ascending letter values). However periods for MY08 are lower than expected for NEHRP class E. In general, site period estimates compare well with estimates by Perez (2005) and reported by Pando et al. (2006). The estimates by Perez (2005) were based on 1-D ground response analyses of several sites where shear wave velocity data was measured using SASW. Perez (2005) analyzed a site in the vicinity of Station MY03. The average value of his site period estimates was 0.53 seconds (based on 5 ground motions and different sets of dynamic properties). This average value from Perez (2005) compares very well with the period estimates shown in Table 3 for this site (average estimate = 0.51 s).




a) Predictions using weak motion earthquakes




b) Predictions using microtremors

Figure 3 Comparison of predominant site periods

## 8. CONCLUSIONS

The suitability of using microtremors and weak earthquake motions for estimating predominant site periods was investigated using recordings from 4 EpiSensor strong motion stations in Mayaguez, Puerto Rico. For each type of ground motions several methods were investigated including two that stem from research efforts of some of the co-authors (Montejo and Suarez, 2006; and Cano, 2008). In general all methods provided reasonably comparable estimates of the predominant site period or frequency. Some methods had better resolution than others facilitating the selection of the predominant period or frequency. Being able to reliably predict predominant site periods from mictremors is an advantage for seismic regions like Puerto Rico where there is a low recurrence rate and there is no strong motion data.

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