The HVSR passive seismic method evaluated in several regions of Brazil

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Abstract

A modern, very compact passive seisimic 3-component instrument was tested in Brazil during January and February, 2017. Calibration for the Sao Paulo sites was possible because wells at the USP IAG test site penetrated bedrock at 53 meters, yielding a shear wave velocity of 450 m/s. This velocity was used to convert resonant frequency for other stations at USP and a nearby park to give estimates of depth to bedrock. Records were very good quality and the H/V ratio gave high-amplitude and well defined peaks. In Sao Luis, the resonance peaks of the H/V ratio were lower in frequency than at SP, and were also broader and had lower amplitude, indicating a much deeper sediment to bedrock transition that was also more gradational than that at SP. Horizontal profiles made from a series of stations at both SP and Sao Luis revealed considerable topography on the basement surface. At the Sao Luis site, a cluster of stations showed double HVSR peaks, indicating an additional shallow boundary; a local 3-layer case. Similar measurements were made near Belem, PA, and in Brasilia, DF. Excellent results indicate that this method functions in diverse environments of Brazil. Most of these measurements showed the pronounced H/V amplitude minimum at approximately twice the frequency of the maximum (f_0). This method shows great promise as a rapid, relatively inexpensive tool for geophysicists to obtain reliable estimates of depth to hard rock in various geologic environments of Brazil.

Introduction

The single station Horizontal-to-Vertical Spectral Ratio technique was proposed by Nakamura (1989) to use microtremors or background seismic noise as a means of measuring the site amplification of earthquake waves, as well as the natural ground frequency to which buildings would be subjected during an earthquake. Many subsequent studies showed that the site amplification was not well determined (Lachet and Bard, 1994). However, the method has had wide and successful engineering use to determine natural oscillation frequencies of buildings, and more important for geoscientists, to determine the natural frequency of soil oscillations and hence the thickness of the soil or unconsolidated layer (Gosar and Lenart, 2010; Ibs-von Seht and Wohlenberg, 1999; Parollai, et al, 2002; Brown, et al, 2013; Chandler and Lively, 2014, to name only a few).

Theory

The original concept of Nakamura (1989) was that SH waves traveling upward through the surficial soil or overburden layer will have a resonant frequency or spectral peak that is related to the shear wave velocity and layer thickness by a simple relationship: $H = V_S/(4*f_0)$. This assumes that the acoustic impedance contrast between soil and bedrock is quite large, more than a factor or 2 or 2.5. Thus, any Body wave approaching this boundary from below will be refracted to nearly vertical (transmitted S wave, or P wave converted to an SH wave) through the soil. The rock-soil boundary can be considered a nodal point for the wave, while the free surface (soil-air) is a quarter wavelength above the hard rock interface or nodal point. Some (Stephenson, 2003) have suggested that the influence of Rayleigh waves (particle motion polarized in the vertical plane) has a major influence on the observed frequency spectrum. His models showed that the Rayleigh wave particle orbits at very low frequencies are retrograde, then become horizontal as the orbits transition to prograde, and at about double this frequency transition again to retrograde with a strong vertical component. This creates the strong H/V peak, followed by a pronounced H/V minimum. However, the minimum is not always present. Nakamura (2008) then defended his original model wherein the H/V resonant peak was due to just the ascending SH wave, while only the trough at $2f_0$ was affected by Rayleigh wave energy. He also insisted that from his studies in Japan, that the site amplification factor could be reliably derived from the H/V peak height, despite less satisfactory results elsewhere in the world.

Method

Prior to about 2000, very few groups could afford to experiment with this technique, because conventional moving-coil, fixed-magnet seismometers did not have sufficient bandwidth to cover the range of frequencies desired, typically from about 0.1 Hz to more than 60 Hz. This required at least two seismometers in each direction (long period and short period), as well as amplifiers and filters for all six instruments. In other words, a truckload of equipment was necessary. With the development of microelectro-mechanical systems (MEMS), broadband seismology was revolutionized. These used a force feed-back system to keep a test mass in a fixed position, thus eliminating the harmonic oscillation of the prior systems, greatly reducing the size, while achieving a usable frequency band-pass of 3 decades or more. A number of 3-component systems are available in a single instrument case. The smaller and more portable ones are the Guralp and Tromino instruments. Common field procedure is to firmly plant the instrument on the earth, via three spike legs, and record N-S, E-W, and Vertical components for a fixed time. The required time is greater when a thick soil layer is present (lower f_0) and less for thin soils, as for the post-processing software to produce some statistical measure of reliability, a minimal number of cycles of the desired signal must be recorded. The instrument was set to digitize at 128 samples per second, and so the maximum possible frequency (Nyquist frequency) that could be analyzed was 64 Hz. Field measure times may range from 10 to 20 minutes, or sometimes even 30 minutes. In Europe, some guidelines suggest that a site should have 3 independent records made, spaced 20 – 30 meters apart.

The post-processing software first calculates the spectra of each of the three components, usually in 20 sec processing windows. This produces, for the example of 18 minute records, 54 independent spectra for each component, which allows averaging and smoothing to be done, as well as calculation of the standard deviations of the amplitudes and frequencies. The next step is to combine the two orthogonal horizontal spectra, point by point. If done in a manner to produce the resultant vector, then directions of polarization (or direction to the source) can be determined with 180 deg uncertainty. Finally, the magnitude of the average Horizontal spectrum is divided point by point by the average of the Vertical spectrum. Amplitude vs. log frequency plots can be made of the 3 spectra; color "waterfall" plots can be produced, showing log frequency on the vertical axis and successive 20 sec processing windows on the horizontal scale that show noise bursts and dominant spectral lines; and then the H/V spectral ratio plot can be displayed, including the standard deviation limits above and below the average ratio plot. Software readily available for this post-processing is the GRILLA package that comes with one instrument, or else the GEOPSY software, a more general purpose processing system. Commonly, the software allows editing of the "waterfall" plot by judiciously removing those windows that contain noise bursts and high-amplitude events that are clearly well above or below the resonance spectral line. Then the remaining data are re-processed to produce sharper peaks and smaller standard deviations.

The conversion of the resonant frequency to Layer 1 thickness is usually done in one of two manners. For small study areas where the bedrock depth is not highly variable, only one or two calibration wells that provide depth to bedrock are needed. Then, shear wave velocity is directly obtained by solving the above expression for Vs, $Vs=4f_0H$. For larger regions where H may vary significantly, and hence deeper and more compacted portions of the upper layer can be expected to have higher velocities, significantly more wells are needed that sample depth to basement over a wide range of H values. For this case, a bi-logarithmic plot is made, with known bedrock depths (soil layer thickness) on the vertical axis, and measured resonance frequencies on the horizontal axis. With a statistically significant number of control wells, this log-log graph will produce a straight line, whose parameters can be solved for by linear regression. The expression for the straight line is $y=ax^b$. As surface layer geology and seismic properties can vary a great deal globally, the constants derived in different studies range from 55 to 360 for "a", and from -1.55 to -0.63 for the "b" exponent. Thickness H is "y", the solution of the above expression.

Results, Sao Paulo

I was able to bring one of these instruments from Western Michigan University to Brazil in early January (as it would otherwise be idle during the winter months with snow cover and frozen ground). In this abstract, results from only two of the four sites will be shown for brevity; Sao Paulo, and Sao Luis. At the University of Sao Paulo, a series of readings was made along a sublinear profile oriented NE, that passed through the Geophysical Test Site of the IAG (Fig. 1). At this site, several test wells penetrated the transition to hard rock at about 53 meters (Porsani et al, 2004), thus providing a calibration point for this area.

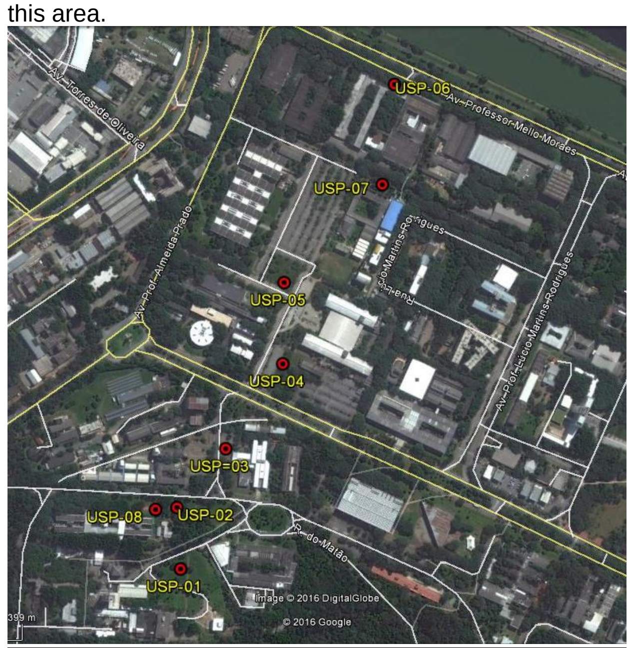

Figure 1: Location map of HVSR stations on the University of Sao Paulo campus. Image from Google Earth.

The resonant frequency was the same at stations near the two wells used for calibration: 2.13 Hz (Figs. 2 and 3). Solving the basic expression for shear wave velocity, $Vs=4f_0H = (4)(2.13/s)(53m) = 451$ m/s. This was somewhat greater than prior experience on glacial drift in Michigan, but could be expected for Tertiary sediments and compact clay-rich soil at the USP site.

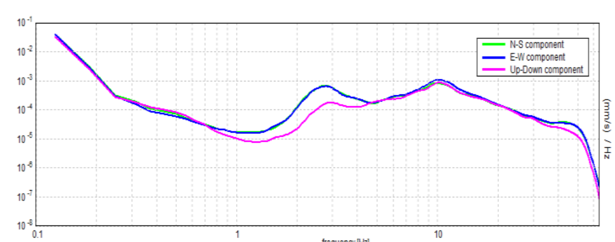

Figure 2: Spectra of the 3 components at Station USP-02, next to an IAG test site well. The two horizontal components are nearly equal. Note the separation between the horizontal and vertical curves at about 2 Hz.

Thus, a value of 450 m/s was used at the other stations on the USP campus to convert the measured f_0 to depth, H.

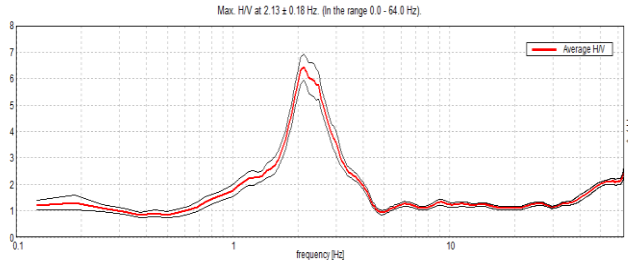

Figure 3: Ratio of the combined horizontal components to the vertical component at USP-02, one of the calibration wells. The strong peak is centered at 2.13 Hz, with Std. Dev. of 0.18 Hz.

The profile of the results of 8 stations, each occupied for 16 minutes, was plotted in Fig. 4. This shows the surface topography, and the elevation calculated for the depth to bedrock at each station (using Vs=450m/s). It shows a bedrock minimum about 200m NE of the IAG building. Note that the last station was occupied less than 20m from the nearest lane of a busy 4-lane divided boulevard, and still gave a clear H/V peak. The H/V ratio for the station with the greatest depth to bedrock is shown in Fig. 5, where the resonant frequency is clearly less than that in Fig. 3.

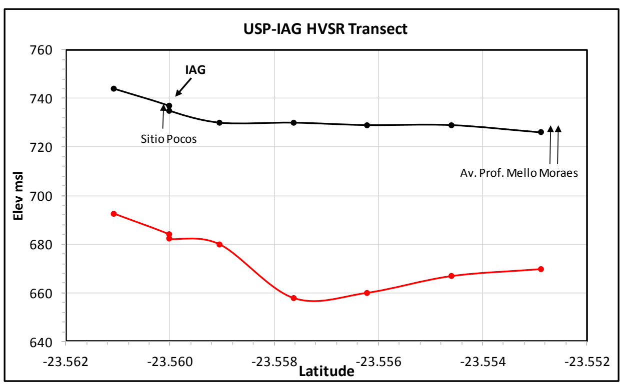

Figure 4: NE-trending profile of HVSR results across part of the Univ. of Sao Paulo campus. Stations have a nominal spacing of about 100m.

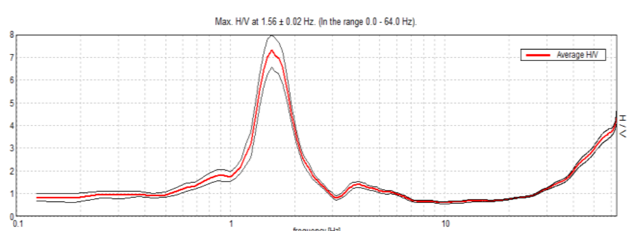

Figure 5: H/V ratio at Station USP-04, showing the lowest resonant frequency along this profile, 1.56 Hz, which led to a calculated depth of 72m. Note the high amplitude peak, as well as the pronounced minimum at about 3 Hz, double the resonant peak frequency.

All of the stations on the USP campus showed a clear minimum of the ratio at about twice the resonant frequency (Figs. 3 and 5), as was discussed in the Theory section that attributed this to a maximum of Rayleigh wave energy. The range of calculated depths along this profile at USP was from 50 to 72 m.

Five stations were also measured at Ibirapuera Park, some 5 km SE of the USP campus. They were distributed in approximately a circular pattern about 1 km in diameter. In general, the record quality was poorer than at USP, as there was considerable local noise due to the presence of several thousand people in the park on New Year's day. Fig. 6 illustrates one of those records, from station IB-04. The Ibirapuera data were recorded for 14 minutes (2 stations) and 16 minutes (3 stations).

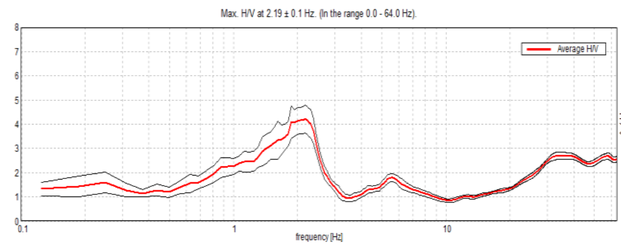

Figure 6: An example of the H/V ratio from station IB-04, Ibirapuera Park in Sao Paulo.

The resonant frequencies were somewhat higher at Ibirapuera than at USP. Using the same velocity for Vs that was determined at USP, the range of depths calculated at these five Ibirapuera stations was from 37 to 55 m.

In summary, for the two sites in the city of Sao Paulo, the University of Sao Paulo site produced very low interference, sharp, symmetric, and high amplitude peaks of the H/V ratio. I was also fortunate at the USP site to have wells to calibrate or measure the average shear wave velocity of the surface layer (450 m/s). The Ibirapuera site had higher local low-frequency noise levels, as can be seen in the left half of Fig. 6, as compared with Fig. 5. The Ibirapuera Park stations all had lower H/V ratio amplitudes and more asymmetric shapes, thus leading to somewhat lower confidence ratings than those at USP. The Park station ratio plots all showed the pronounced low at about twice the resonant peak frequency.

Results, Sao Luis, MA

A series of eleven measurements was made along a nearly W-E transect at the eastern end of Sao Luis Island, Maranhao. Additionally, five were made along an arc of Itapary Beach, all at the high tide line. These stations were occupied for 20 minutes, as the resonant frequency here was significantly lower than in Sao Paulo and thus requires a longer measure time. A typical H/V spectral ratio curve is shown in Fig. 7 for station SLZ-03. This clearly shows a lower resonance frequency than any of the Sao Paulo sites, in this case, 0.63 Hz.

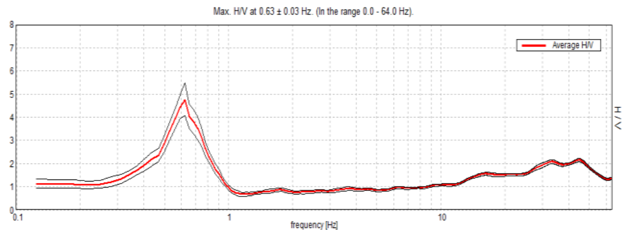

Figure 7: H/V ratio at Station SLZ-03 showing a clearly defined, but lower amplitude peak at 0.63 Hz.

Another way of displaying the results is in the form of a "waterfall" plot, log frequency vs. time in 20 second processing windows. An example is shown for this station in Fig. 8.

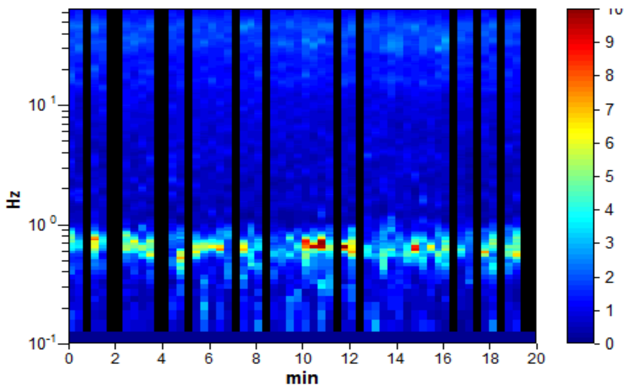

Figure 8: H/V Frequency vs. time plot for Station SLZ-03, displaying 20 second processing windows after editing removed some windows containing noise bursts. The spectral H/V peak at 0.63 Hz is clearly visible.

A feature not seen in the Sao Paulo records was the two-peak response of seven of the Sao Luis records. As the higher-frequency peaks do not have a common frequency (ranging from 3.9 to 5.6 Hz), they can not be ascribed to a local coherent noise source (also unlikely in this remote area). The high-frequency peak is most likely due to a shallow transition to higher Vs, in other words a three-layer case is probable below these seven stations. One of these records is shown in Fig. 9. Using an assumed Vs of 400 m/sec, the depth calculated to the upper interface

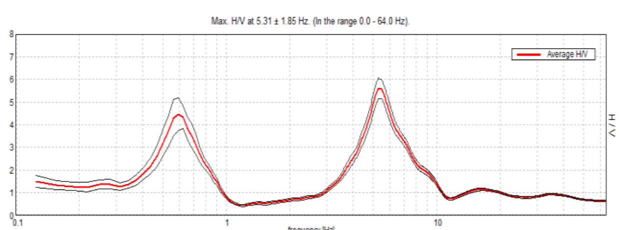

Figure 9: An H/V spectral ratio curve at Station SLZ-05, showing two resonance peaks. The lower frequency peak is typical of all 16 stations, and is 0.59 Hz at this location. The higher peak (here 5.31 Hz) was found at a cluster of other stations near and along the beach.

ranged from 18 to 25 m. Meanwhile, the deeper, more regional boundary depth estimates ranged from 159 to 213 m. The amplitude of the higher-frequency peak diminished to the west, away from the beach, and also to the ENE and to the WSW along the beach, indicating that this is a local feature with limited lateral extent. Fig. 10 shows an example of the spectral ratio curve where the higher frequency peak was no longer dominant. When compared with Fig. 9, the overall peak amplitudes are lower, and the right peak has lower amplitude than the left peak.

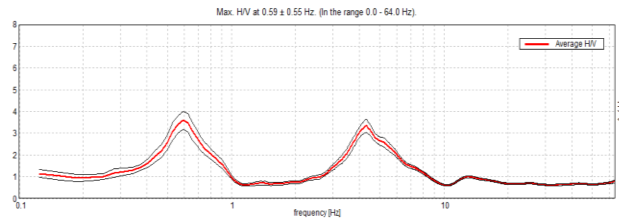

Figure 10: Station SLZ-07, showing a diminished amplitude for the higher-frequency peak. The spectral peaks were at 0.59 and 4.29 Hz at this most ENE station of the survey. Note the same broad peak response, as well as the sharp minima at about twice the resonant frequencies.

Fourteen of the stations were aligned along a W-E rural road, which turned to the ENE near the coast and continued with the last three stations along the beach. There is a bluff of 12-15 m at the shoreline, where sub-horizontal strata of the Tertiary sediments, typical of the Para-Maranhao coastal region, can be clearly seen. This transect, 3.2 km long, is shown as Fig. 11. It shows a general increase in depth to the velocity boundary towards the west (interior of Sao Luis Island). There are two local minima, at 950 and 2000 m along the transect.

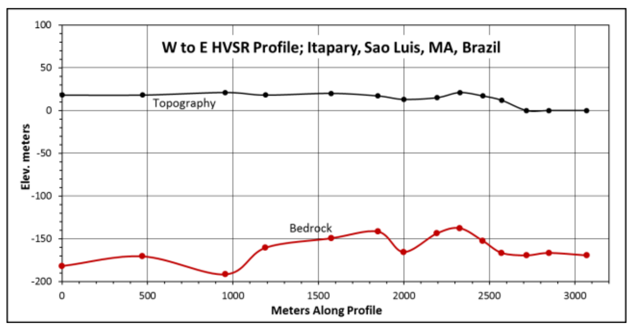

Figure 11: Results of the H/V ratio measurements along an E-trending transect that turned to ENE at 1700 m along the transect. The last three stations were on the beach. Depths were estimated using an assumed Vs=400 m/s.

If these two minima are real, these could indicate some erosional topography at an unconformity. The three stations at the right end of the transect show a very smooth or consistent depth to the Vs boundary. This could also be a function of uniform quality of the instrument placement. At the beach stations, all were dug 20 cm into sand and the instrument was firmly "planted" in cohesive wet sand, which was also packed around the sides of the instrument. In HVSR work, the quality of the instrument contact with the earth is highly important; it cannot simply be placed on loose soil.

The station SLZ-05, on the beach at the high-tide line, was repeated two days later. The first reading (Fig. 9) was done near high tide, and the second (Fig. 12) during low tide, when the water's edge was more than 200 m away. In both cases wave action was minimal. The repetition was done to show the temporal stability of the method, as well as to discount any effect of local tide or wave action. The spectral curves, and their ratios were visually identical, and yielded the same H/V ratio resonant peak at 0.59 Hz and nearly the same at 5.63 Hz.

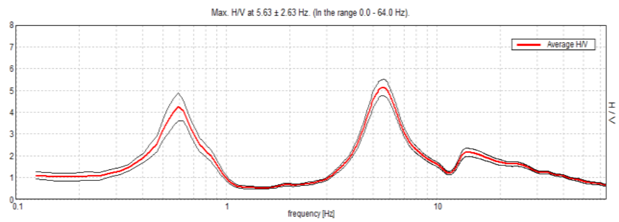

Figure 12: Spectral ratio curves for station SLZ-05R, a repeat of measurement SLZ-05, but two days later. Compare with Fig. 9.

Returning to the same station after two days, when weather and tidal conditions were different, and obtaining effectively the same results leads to great confidence in the method and in the measuring instrumentation. Good science is repeatable.

Conclusions

A compact, new instrument for measuring three orthogonal components of background seismic noise, or microseisms, was tested at four sites in Brazil in early 2017. A transect of stations was done at the Univ. of Sao Paulo where wells with a known depth (53 m) to hard rock were available for determination of the shear wave velocity. The average Vs was calculated to be 450 m/s. At the Ibirapuera Park site, five additional stations were measured. In total, 13 stations were occupied in Sao Paulo, and they produced depths to hard rock that ranged from 37m to 72m.

Sixteen stations were surveyed at the eastern end of Sao Luis Island, MA, plus one repeat observation. All of these showed a deep boundary, ranging from 159 to 213 m in depth, or more than twice the depths found in Sao Paulo. Additionally, seven of the stations showed two resonance peaks, the higher of which is likely related to a much shallower local Vs increase at depths ranging from 18 to 27 m.

Almost all of the Sao Paulo and Sao Luis records showed a clear minimum at about twice the resonant frequency. This was discussed earlier with respect to the involvement of Rayleigh wave motion in contributing to the H/V ratio curve features (in addition to the usually assumed dominance of the SH motion).

Interesting, coherent, and repeatable results were obtained in all four regions tested (two of which were described in this abstract). The regions represent quite different geologic and climatological environments.

This method requires only one operator in the field, and only a GPS device for providing the location. Elevation can be obtained by differential GPS, or in many areas Google Earth is sufficient to give elevation within a meter or two. The HVSR method is far less expensive than seismic refraction or reflection surveys. While it does not replace them, it can be used to give important information about the subsurface with minimal effort. A simple garden tool may be needed to scrape aside loose soil and expose cohesive soil. In fact most of the time in the field is spent by waiting quietly. Bring a good book!

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