Università degli Studi di Padova

Seismic Noise Assessment & Network QC on Single Station 3-Component Velocimeters

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Vishnuraj Sreeraj Nair

Supervised by:
Prof. Jacopo Boaga
Dr. Alessandro Brovelli (External)

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DIPARTIMENTO
DI GEOSCIENZE

In the loving memory of my grandfather V. G. Sreedharan Nair
(1937 - 2023)

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Vishnuraj Sreeraj Nair
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Abstract

Seismic noise characterization and quality control are important components of seismic monitoring network management, particularly when three-component seismometers are used. This study presents a novel approach to achieving both objectives using the directional horizontal-to-vertical spectral ratio based on the Nakamura Technique.

In this thesis, we present a comparative framework and a new method for evaluating the performance and reliability of three-component velocimeters. Our method uses DHVSR, a powerful tool that takes advantage of the recorded ground motion between the horizontal and vertical components of the seismometer to determine its health and performance, as well as to characterize the ambient noise wave field on site. We used field data to analyze the effectiveness of this method and deployed a Network of Seismic Stations based on the lessons learned from this research project.

Furthermore, the proposed method not only provides valuable insights into the seismic noise characteristics of monitoring stations but also provides a robust quality control method for the 3-component seismometers used in the network.

In addition, this new approach improves the overall performance of a seismic network by facilitating real-time monitoring and a rapid response to changes in noise conditions. Our findings demonstrate significant improvements in the reliability and efficiency of seismic data collection and analysis.

In conclusion, our study presents a quantitative approach for rapid and automatic seismic noise characterization and network quality control, specifically designed for the long-term deployment of short-period three-component seismometers.

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Part One

Introduction

Seismic noise assessment and network quality control (QC) play an important role in the reliability and accuracy of seismic data collected by single-station three-component short-period velocimeters (hereafter referred to as seismic station or seismometer). These instruments are designed to record ground motion in three distinct directions (north-south - east-west -vertical), similar to a three-component geophone, but seismographs can understand various seismic signatures, from local earthquakes to long-range earthquakes and human-induced activities, record, store, digitize them, and transmit them to monitoring/processing stations.

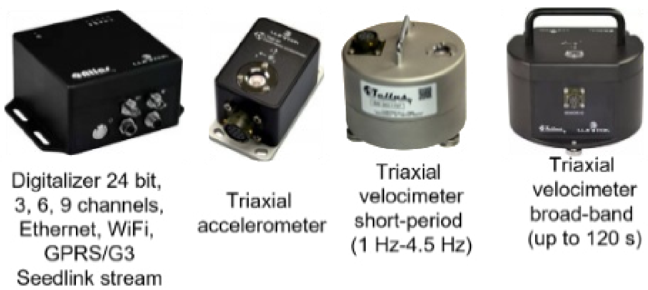


Figure 1: Examples of Seismic Instruments

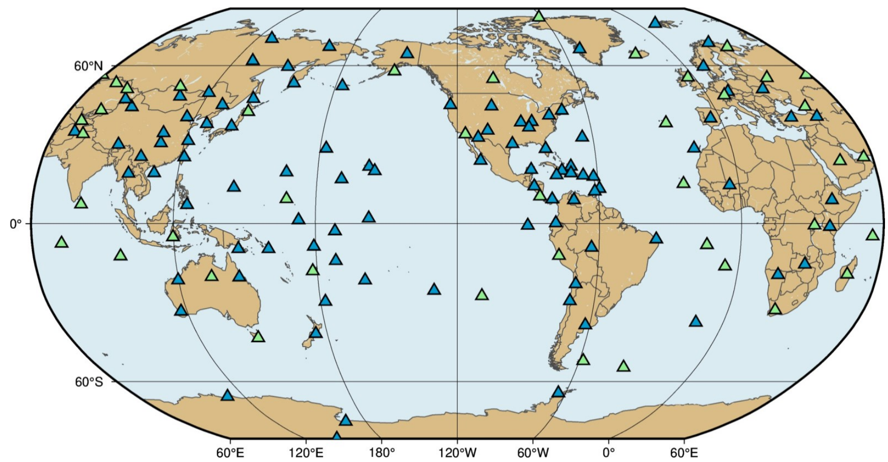


Figure 2: Global Seismic Network (GSN), a US based seismic network for Earthquake Detection (Photo from: (GSN Website)

Seismographs have played a very crucial role in many fields of human development since the start of the 20th century, and today we have a large network of seismic stations scattered across the globe for different uses.

Some prominent uses include:

Earthquake Detection and Noise Analysis, Earthquake Forecasting, Landslide Forecasting, Structural and Civil Engineering use, Geological Storage monitoring, Nuclear bomb detonation detection, Ensuring risk-free geothermal exploration, Oil and Gas detection and production, etc. [Global Earthquake Monitoring, Its Uses, Potentials, and Support Requirements - 1977]

From the aforementioned uses, we can estimate the importance and dependence of seismographs. For the same reason, it is of utmost importance to perform regular quality control (QC) and inspection of seismographs to ensure that correct data are being recorded. Incorrect or noisy data severely distort the quality of further processing and can give results that are completely different from the real-world case and can lead to catastrophe in sensitive projects such as the storage of Nuclear waste!

A seismograph can produce incorrect or noisy data for three main reasons:

1. Instrument Failure
2. Ground sensor coupling issues
3. Ambient Seismic Noise

This research thesis proposes a new method that can detect and give us some insights into which of the above issues is the reason for incorrect/noisy recording. However, the focus of this research is mostly on ambient seismic noise.

Part Two

Ambient Seismic Noise Analysis

Seismometers were initially developed for measuring ground motion to detect or possibly forecast events such as earthquakes and volcanic eruptions. However, it was observed that the seismometers continued to record vibrations produced by the Earth, which were of relatively low frequency but omnipresent [Schimmel, M., et. 2011] [Nishida, K. - 2017]. These ambient seismic noises were categorized into three, (a) Seismic Hum with frequencies ranging between 1 and 20 MHz; (b) Microcosmic: with frequencies ranging from 0.02 to 1 Hz, and (c) Microtremor: with frequencies ranging from 0.5 to 20 Hz [Nakamura, Y. - 1989].

Microseisms are further categorized into two, (a) primary microseisms, with a range between 0.02 and 0.1 Hz, and are strongest at 0.05 Hz to 0.08 Hz, and (b) secondary microseisms, with a range between 0.1 Hz to 1 Hz, and are strongest between 0.1 and 0.16 Hz. Secondary microseisms dominate the ambient-noise wavefield. [Hasselmann, K. - 1963][Nishida, K. - 2017][Nishida, K. - 2017]

Microtremors, which occur at a higher frequency than microseisms, were much more important in this study. Ideally, we can consider any frequency of about 1 Hz as a micro-tremor, and the range 0.5 - 20 Hz comprises both Human induced and Naturally sources waves. According to earlier research conducted by Nakamura (1989), the effect of micro-tremors induced by human activities is lowest between 2 am and 3 am.

In industry and even in academia, there is still ambiguity between the distinction of Seismic Hum, Microseisms and Microtremors, and a broader term “Ambient Seismic Noise” or “Seismic background noise” is generally used. However, the effects of Seismic Noise were not unseen, and were treated as external vibrations and turbulence in the Earth’s crust that interfered with interesting seismic signals. Hence, they were generally removed or filtered from the actual records. Further, Seismologists created high-frequency sensors (Short period) with corner frequencies higher than 1 Hz and low-frequency sensors with average frequencies lower than 0.1 Hz (Long period) to avoid the bigger amplitudes of the ambient noise [Nishida, K. - 2017]. The effect of these propositions can still be observed; in many countries, by law, a seismometer with a corner frequency higher than 1 Hz is still used for seismic monitoring.

The Source of Ambient Noise has been debated for years, but from existing research, we can conclude that below 1 Hz, the dominant source of ambient noise is oceanic gravity waves. Many studies have discovered changes in the ambient noise wave field below 1 Hz related to ocean swell, oceanic infra-gravity waves, wind waves, and even seasonal variation [Nishida, K. - 2017]. The Source of Ambient Noise above 1 Hz is mainly linked to human activities or is induced by structures such as trees and buildings [Bonnefoy-claudet, S., - 2006]. This is one of the reasons for the development of new supporting methods for characterizing the Ambient Noise. With expansion of Human activities, the level of Ambient noise higher than 1 Hz is also increasing [Bonnefoy-claudet, S., - 2006], and the monitoring equipments are still the same with conner frequency of 1 Hz, i.e. we cannot fully trust the data recorded below 1 Hz.

Hence, a comprehensive ambient noise analysis is necessary to identify noise sources and their characteristics to improve the quality of the data and help fulfill its goal seamlessly.

Some of the steps in seismic noise analysis include the following.

1. Noise characteristics: Analysis of the spectral characteristics of noise at different time scales to identify dominant frequency patterns.

2. Signal-to-noise ratio (SNR) analysis: Analysis of the ratio of seismic signal amplitude to noise level to determine the long-term data quality.

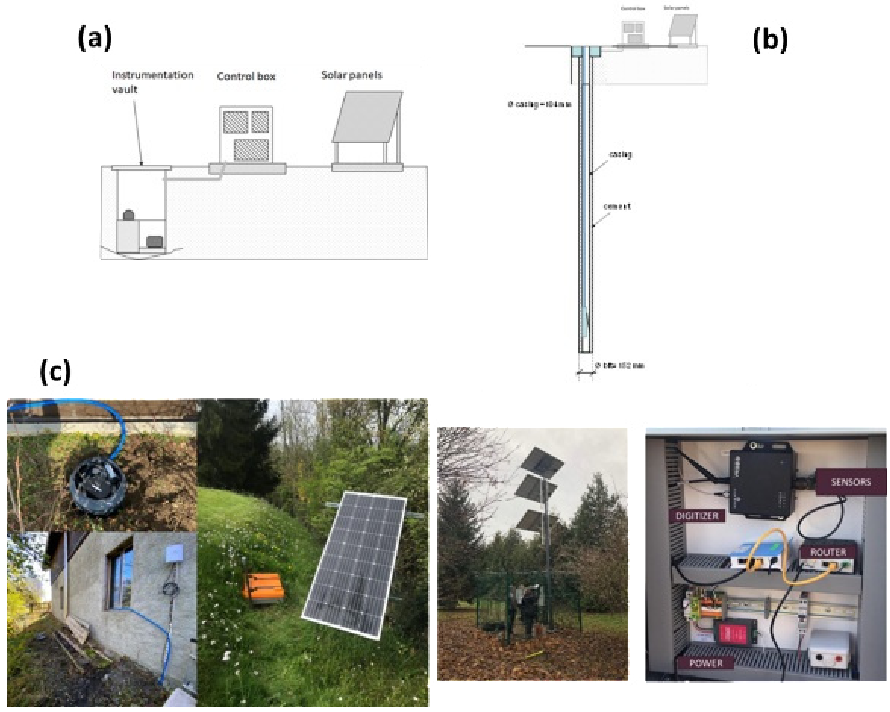
3. Noise source identification: Identification and classification of noise sources by correlation with external factors (weather and traffic) and visual observations.

4. Noise Reduction: Implement various noise reduction techniques, such as the use of bandpass filters, spatial averaging, or scheduled programming

Further, Network Quality Control (QC) on Single Station 3-Component Short Time velocimeters is essential for maintaining the integrity and reliability of seismic data collected in a network of stations, including inspections and procedures to ensure that devices are working properly and providing accurate data.

Some of the QC methods include:

1. Data Completeness: Ensures that the station always records and transmits data, as expected.
2. Sensor Calibration: Regularly calibrating 3-component accelerometers ensures the accurate measurement of ground motion.
3. Time Precision: A time series for determining the accuracy of the time stamps of earthquake events.
4. Monitoring noise levels: Noise levels are monitored over time to detect any changes or abnormalities that may affect the data quality.
5. Events and location: Assessing the ability of a station to accurately detect seismic events.



3: Schematic view of a surface and deep (micro)seismic monitoring station in and (a), (b), respectively. In (c) some examples of the station installation using solar panels for the power supply

Part Three

A Brief History of Ambient Seismic Noise

The history of Ambient Seismic Noise of course begins with the history of Earthquakes. Since ancient times, we have referred to earthquakes in various parts of the world.

Figure 4: Representation of Seismoscope invented by Zhang Heng

However, the Chinese inventor Zhang Heng in 132 AD is credited with the first theoretical reference to an earthquake measuring device called Seismoscope. It was a bronze vessel with eight dragons built around its rim, facing eight directions, and holding a metal ball. When the earthquake uses d to hit the device, the ball falls from the dragon’s mouth to the metallic plate placed below, creating sound. If such a device exists, is still unclear. In any case, let us fast forward ourselves into the modern world. The first evidence of a recorded earthquake with a Seismoscope in Astronomical Observatory of Parma, Italy. In 1872, Bertelli observed the movement of a Tromometer, a pendulum-based Seismoscope, in relatively quiet periods and correlated its motions with long-period noise generated by disturbed Air Pressures.

In 1911, Gutenberg carried out an extensive and major review of the origins of microseisms, which was further correlated with meteorological conditions by researchers such as Banerji. Bernard (1941) and Longuet-Higgins (1950) observed the relationship between Microseisms and Ocean swells.

One of th biggest turning points in the history of Ambient noise occurred when in 1971 Nagoshi and Igarashi proposed the foundation for a technique called as "Horizontal-to-Vertical Spectral Ratio" (which will also serve as the conner-stone for this Thesis paper),"HVSR" in short, which was popularized by Nakamura in 1989. HVSR has quickly gained popularity, especially in site response analysis and microzonation studies. Furthermore, Seismic Ambient Noise has been extensively studied by the SESAME European Project, which remains among the largest studies on Seismic Noise.

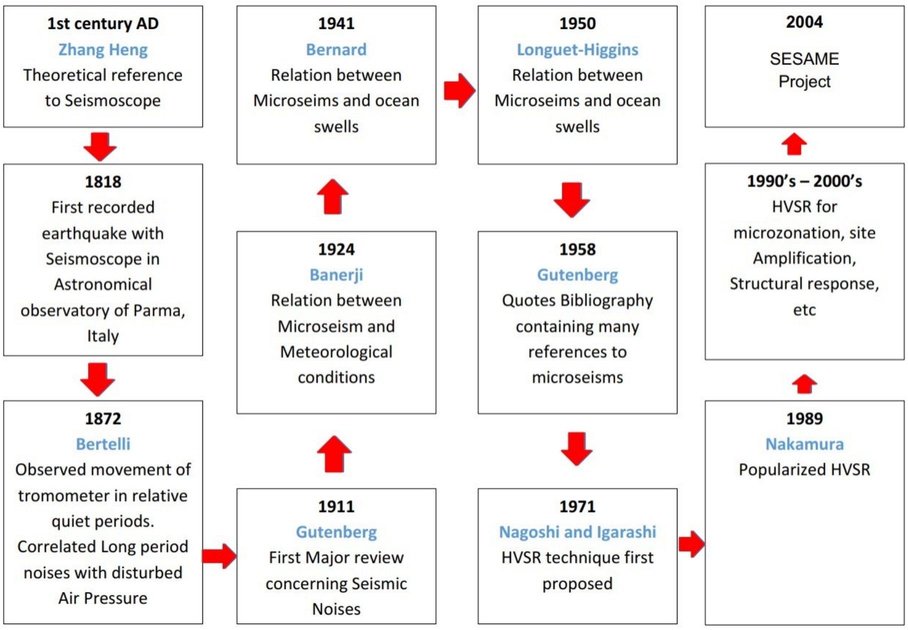


Figure 5: Some Important events in the history of Ambient Seismic Noise Study

Part Four

Aims & Objectives

The Aim of this research is to develop a new method that will not necessarily replace but rather support existing methods for Ambient Seismic noise Analysis and Quality control of long term deployed short-period seismometers.

The objective includes:

1. Development of New method for Ambient noise characterization and verify its results
2. New developed method should also be able to perform QC inspection on seismometers with short periods
3. New method develop should be able to work with existing infrastructure already in use
4. Compare the results produced by New method with the existing methods
5. Produce Guidelines, scripts, and other supporting material to increase the efficiency of existing QC methods

Part Five

Existing QC methods and their Drawbacks

Probability Power Spectral Density (PPSD)

The probability power spectral density (PPSD) is a mathematical technique for determining the random process or power spectral density of a signal in the frequency domain. This provides valuable insight into the signal power distribution as a function of frequency.

The traditional power spectral density (PSD) represents the power of a signal or process as a function of the frequency. It is usually calculated by considering the Direct Fourier transform of the autocorrelation function of the signal; but, while analyzing the data using Power Spectral Density we must considered and the limitation imposed upon this technique – that the collected data has to be stationary [Łacny, Ł., Ścisło, Ł., & Guinchard, M. - 2020]. However, in some cases, the signals may exhibit changes over time, and their spectral properties do not remain constant. In such cases, the probabilistic power spectral density captures the statistical variability of the PSD using the probability distribution of the power spectral density at each frequency considered [McNamara and Buland - 2004].

The concept of probability power spectral density may be particularly relevant to seismic noise analysis. This enables seismologists and researchers to study how earthquake noise intensity can occur at different frequencies, thus gaining a clearer understanding of noise properties and changes over time. Furthermore, by analyzing the intensity, seismologies can guess if they are issues with the sensor, sensor-ground coupling, or change in ambient noise wave field. Apart from QC, PSD and PPSD are also used as replacements for the STA/LTA method for earthquake detection. It has been found that with PSD, events of far smaller magnitude can be detected [Vaezi, Y., & van der Baan, M. - 2015]. Thus, it is a very powerful and reliable technique that has been used for Seismic Network QC worldwide.

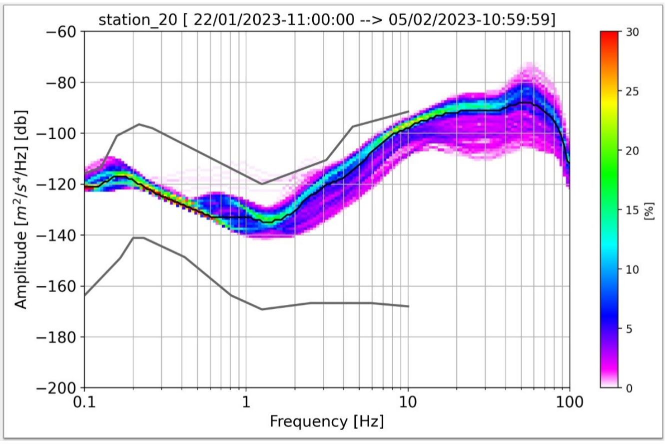


Figure 6: An Example of PPSD Curve

Other Methods

Some of the other methods used for QC of Seismic stations and seismic noise analysis are as follows:

RMS

The root mean square (RMS) is an important measure of the signal amplitude or strength and is widely used in signal processing and seismic monitoring. The RMS statistic indicates the strength of the seismic signal within a particular time window. It is used for noise level characterization, Temporal Variation in ambient noise, and frequency analysis such as PSD. ["Digital Signal Processing" by John G. Proakis and Dimitris G. Manolakis]

Beamforming

This method is used to determine the route or location of the source of the seismic waves. This method mixes records from more than one seismic sensor (geophones or seismometers) to increase the signal-to-noise ratio (SNR) and pinpoint the beginning of seismic events. Beamforming is used to localize earthquakes, detect and read ground motions, and study the characteristics of seismic resources.

Azimuthal Gap

Angular separation of seismic stations that recorded a particular earthquake. Specifically, it measures the spatial distribution of the recording sites where an earthquake occurred. Azimuth is an important parameter used in seismic studies and research, especially in statistically and quantitatively determining the accuracy and reliability of the seismic zone.

Drawbacks

Although probability power spectral density (PSD) is a valuable tool for seismometer QC and noise characterization, it has some drawbacks and limitations.

First, it is more of a visual tool; hence, the interpretation can change from person to person depending on the experience and knowledge one has. It provides a quantitative value of the frequency distribution, and it is not sufficient to check the overall health of the station. Furthermore, the frequency values can change for multiple reasons. Let us say there is a new structure constructed in the vicinity of the seismic station that has changed the pattern of the ambient seismic wave field in the area. By looking just at the data, we will not be able to guess if the issue is due to the change or if the equipment is malfunctioning. It may not sound much, but for a company monitoring data from a distant location, it can have a huge economic impact. In addition, small data processing steps or parameter choices can impact the PPSD graph, which further depends on the person performing the processing.

Similar issues can be observed with the RMS method, particularly its sensitivity to noise. The RMS method computes the square root of the squared mean in a time window. The presence of impulsive noise can significantly affect the squared amplitudes, rendering the RMS measurement inaccurate. Further, this method only considers the amplitude of the seismic signal and does not provide any information about its “Phase.” Phase information can be important for a variety of seismic applications such as determining the direction of waves or detecting seismic events.

The other methods, Beamforming and Azimuthal Gap can only be applied on a network of Seismic stations. However, this study focuses on a single seismic station, and thus, we do not consider them.

Part Six

The Nakamura Technique

The horizontal-vertical spectral ratio (HVSR) method, also known as the Nakamura technique/method, is a seismic survey technique used to calculate the fundamental resonance frequency (peak natural frequency) relative to the seismic noise or soil at a particular location. This method is particularly valuable for identifying areas where ground motion is amplified, assessing soil properties, and understanding the response of geologic features to seismic waves [Nakamura, Y., - 1989] [Gutenberg]. As the name suggests, Nakamura, Y., popularized this strategy, which was first put fourth by Nogoshi and Igarashi (1971) based on the initial studies of Kanai and Tanaka (1961), for site effect study, and it offers fresh approaches and ideas for numerous research fields. However, the initial intent was to assess site effects using the Fourier amplitude spectrum ratio of the horizontal and vertical ground pulsation components at the same surface measurement point. HVSR has gained a lot of popularity despite being predicated on several assumptions because of how straightforward site data collection and signal processing are [Xu, R., & Wang, L., - 2021]. Furthermore, it does not require any modeling and gives two values apart from the H/V curve:

1. Fundamental Site Frequency (f0)
2. Corresponding Amplitude

Method Details

The HVSR method measures the ratio of horizontal ground motion (usually north-south and east-west) to vertical ground motion (usually recorded by a vertical seismic line) over a frequency range. The HVSR method is based on the assumption that the ground motion frequency amplifies the ground motion in the horizontal direction, resulting in a peak in the HVSR curve at that frequency [Nakamura, Y.,-1989].

Steps for HVSR analysis:

1. Data Collection: Seismic data were collected from horizontal and vertical seismic records in the area of interest. These data often include a time series of ground motion records.
2. Preprocessing: Data preprocessing steps, such as detrending and filtering, can be used to remove unwanted noise and improve the quality of seismic data.
3. Fourier Transform: Seismic data are transformed from the time domain to the frequency domain using Fourier transform. This step allows the analysis of ground motion at different frequencies.
4. HVSR calculation: The HVSR is calculated by dividing the Fourier amplitude spectrum of the horizontal ground motion by the Fourier amplitude spectrum of the vertical ground motion for each frequency bin.

$$HVSR_S = H_S/V_S$$

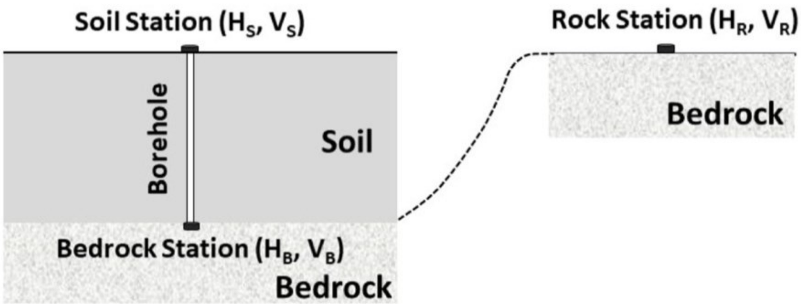


Figure 7: Diagram of soil, reference rock & bed rock recordings [Diagram by Xu, R., & Wang, L. (2021)]

The proposal of HVSR is based on two assumptions:

$$HVSR_B = H_B/V_B = 1 \text{ and } TF_V = V_S/V_B = 1$$

Where, H_B and V_B represents the spectral of Horizontal and Vertical components, V_B and V_S represents the amplitude spectra of vertical component at bedrock and free surface, and TF_V is the vertical transfer function. Similar to Vertical transfer function, we have horizontal transfer function $TF_H = H_S/H_B$

Therefore, from the aforementioned equations we can write:

TFH = HS/HB = (HS/VB)*(VS/VB)*(VB/HB) = HS/VS = HVSRS

As TF_H = $HVSR_S$, we can say that $HVSR_S$ can be used as an alternative transfer function

Similarly, there is also a consencus that HVSR is similar to TF, the empirical transfer function and thus it can be used to get fundamental frequency (f0) in site[Xu, R., & Wang, L., - 2021] [Nakamura, Y., - 1989].

1. Plotting the HVSR curve: The resulting HVSR values were plotted as a function of frequency to form the HVSR curve. This curve typically exhibits a peak at the lower fundamental resonance frequency.
2. Resonant frequency estimation: The frequency at which the HVSR curve reaches its maximum value corresponds to the fundamental resonant frequency at the location. These frequencies can be used to characterize the soil and geological features of the site.

Importance and Application

The HVSR method has several important applications in seismology, civil engineering, structural engineering, and geotechnical engineering.

1. Site Characteristics: HVSR analysis helps assess the geotechnical properties of the site. Knowledge of the fundamental resonance frequency of a site is important for understanding its seismic response to seismic waves.
2. The Seismic hazard assessment: Understanding site-specific ground motion amplification is important for seismic hazard assessments and building codes. HVSR results contribute to the development of seismic design parameters.
3. Infrastructure planning: Engineers and planners use HVSR data to make informed decisions about constructing critical infrastructure such as buildings, bridges and pipelines in earthquake-prone areas
4. Soil erosion detection: HVSR is effective for detecting the presence of soil erosion or low soil erosion, which

can significantly amplify seismic waves and affect the stability of structures.

Furthermore, many empirical formulations and uses have been developed Using HVSR, such as obtaining the thickness of the sediment layer, using HVSR in multilayer sites, and obtaining the depth of bedrock. [Malte, by. - 1999][Sánchez-Sesma, et. -2011]

Part Seven

Our Approach

Our Approach to Seismic Noise Characterization and Seismometer Quality control is simple and empirical in nature. We attempted to develop a new method and guidelines using the horizontal-to-vertical spectral ratio as the cornerstone. The following are some of the reasons for this.

1. Easy deployment and processing: First, the proposed method can be applied to existing networks irrespective of the corner frequency of a seismograph. Ideally, a long-period broadband seismometer should be considered a Gold-star for HVSR acquisition. The acquisition is carried out to obtain the fundamental frequency of the site; however, the goal with the obtained f0 values is to check the reliability and consistency of the equipment on the side. Furthermore, the processing is relatively easier and cheaper, as we have developed with open-source software and Python scripts.

2. We have developed methods to understand the site ambient noise wave field in a much more intimate way, such as obtaining a rough estimate of the direction of the wave field, than existing methods. The more information and understanding we have about the site, the better it is for us to rectify and eliminate problems that will arise.

3. We have tried to develop a quantitative matrix for seismometer quality control, which makes it easier to interpret and explain the issue to a client, with little or no knowledge to interpret a visual QC tool such as PPSD.

Part Eight

The SESAME Project

The European Research Project Site Effects Assessment Using Ambient Excitations (SESAME) Contract No. EVG1-CT-2000-00026), which was operational from to 2001-2004 could be, undoubtedly considered one of the biggest research projects on the H/V Spectral Ratio. It brought together about 14 universities and research institutes, and many researchers are motivated to develop reliable analytical methods, procedures, and techniques for earthquake hazard abatement and risk mitigation.

The project was highly successful and changed the outlook on the ambient seismic noise. It has developed many guidelines and recommendations that still serve as the basis for nearly all H/V spectral ratio studies and software. Further, they developed a dedicated software “J-SESAME” which aimed to standardize the different processing routines. It was developed using the Java programming language to provide platform-free operational capacity. J-SESAME software was designed around a user-friendly graphical user interface (GUI), providing extensive functionality to the user. [13] [14]

This study, uses the findings and guidelines of the SESAME project as the conner-stone.

Criteria for a reliable H/V curve

i) $f_0 > 10 / l_w$

and

ii) $n_c(f_0) > 200$

and

iii) $\sigma_A(f) < 2$ for $0.5f_0 < f < 2f_0$ if $f0 > 0.5Hz$

or $\sigma_A(f) < 3$ for $0.5f_0 < f < 2f_0$ if $f0 < 0.5Hz$

Criteria for a clear H/V peak

(at least 5 out of 6 criteria fulfilled)

i) $\exists f^- \in [f_0/4, f_0] \mid A_{H/V}(f^-) < A_0/2$

ii) $\exists f^+ \in [f_0, 4f_0] \mid A_{H/V}(f^+) < A_0/2$

iii) $A_0 > 2$

iv) $f_{peak}[A_{H/V}(f) \pm \sigma_A(f)] = f_0 \pm 5\%$

v) $\sigma_f < \varepsilon(f_0)$

vi) $\sigma_A(f_0) < \theta(f_0)$

- l_w = window length
- n_w = number of windows selected for the average H/V curve
- $n_c = l_w \cdot n_w \cdot f_0$ = number of significant cycles
- f = current frequency
- f_{sensor} = sensor cut-off frequency
- f_0 = H/V peak frequency
- σ_f = standard deviation of H/V peak frequency ($f_0 \pm \sigma_f$)
- $\varepsilon(f_0)$ = threshold value for the stability condition $\sigma_f < \varepsilon(f_0)$
- A_0 = H/V peak amplitude at frequency f_0
- $A_{H/V}(f)$ = H/V curve amplitude at frequency f
- f^- = frequency between $f_0/4$ and f_0 for which $A_{H/V}(f^-) < A_0/2$
- f^+ = frequency between f_0 and $4f_0$ for which $A_{H/V}(f^+) < A_0/2$
- $\sigma_A(f)$ = "standard deviation" of $A_{H/V}(f)$, $\sigma_A(f)$ is the factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided
- $\sigma_{logH/V}(f)$ = standard deviation of the $\log A_{H/V}(f)$ curve, $\sigma_{logH/V}(f)$ is an absolute value which should be added to or subtracted from the mean $\log A_{H/V}(f)$ curve
- $\theta(f_0)$ = threshold value for the stability condition $\sigma_A(f) < \theta(f_0)$
- $V_{s,av}$ = average S-wave velocity of the total deposits
- $V_{s,surf}$ = S-wave velocity of the surface layer
- h = depth to bedrock
- h_{min} = lower-bound estimate of h

Threshold Values for σ_f and $\sigma_A(f_0)$

Frequency range [Hz]	< 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0
$\varepsilon(f_0)$ [Hz]	0.25 f_0	0.20 f_0	0.15 f_0	0.10 f_0	0.05 f_0
$\theta(f_0)$ for $\sigma_A(f_0)$	3.0	2.5	2.0	1.78	1.58
$\log\theta(f_0)$ for $\sigma_{logH/V}(f_0)$	0.48	0.40	0.30	0.25	0.20

Figure 8: Criteria for Reliability of Results [From: SESAME]

Part Nine

Software and Packages Available

Geopsy

Geopsy is a software package designed to analyze geophysical data. It is commonly used in seismic and geotechnical industries for a variety of applications, including seismic data generation, environmental vibration analysis, site characterization, and seismic hazard assessment. It provides various tools and products for researchers and professionals in these industries. It was released in 2005 as one of the outcomes of SESAME and was also developed by the SESAME team [Wathelet, M., et. - 2020]. This produces nearly the same results as J-SESAME [Gospodinov, D., et. - 2018]; hence, owing to better GUI experience, we used geopsy for our experiments.

Key features and capabilities

1. Seismic data processing: A biopsy enables users to import, process, and visualize seismic data. It supports a variety of seismic data formats and provides filtering, decimation, and other pre-processing tools.

2. Ambient Seismic Analysis: Geopsy is well known for its ambient seismic analysis capabilities, including horizontal-to-vertical spectral ratio (HVSR) calculations, single-station ambient noise measurements, and microseismic analysis, which determine site effects. The sound of the site is calculated and considered to be a seismic hazard.

3. MASW (multichannel analysis of surface waves): Geophysics includes tools for MASW analysis, which is a geophysical method for determining shear wave velocity profiles in the subsurface, which is important for investigating and understanding soil properties in seismic data location response.

4. Cross-hole and down-hole seismic testing: Geopsy supports cross-hole and down-hole seismic testing data analysis, helping researchers and engineers obtain valuable subsurface data for geotechnical and seismic

studies

5. Geotechnical and Seismic Site Characterization: The software helps characterize soils and rocks, analyze soil thickness, and determine seismic velocities for geotechnical engineering and seismic hazard analysis

6. Geomotion analysis: Geoscience enables the analysis of recorded ground motion related to seismic events, helping researchers understand the forces of shaking and its effects on buildings and land

7. Spectral Analysis: The software provides tools for spectral analysis, including the calculation of power spectral density (PSD), which is essential for understanding the frequency content of seismic signals

8. Open-Source: Geopsy is an open-source software that makes it available to a wide variety of people and allows for community contributions and improvements.

hvsrpy

hvsrpy is a Python package developed by Joseph P.. Vantassel, with contributions from Dana M. Brannon under the supervision of Professor Brady R. Cox at The University of Texas at Austin and is a dedicated package developed for the horizontal-to-vertical spectral ratio. The package has also been developed using the SESAME criterion and produces similar results to geopsy [Joseph Vantassel, 2020]; however, it has a few upgrades:

1. hvsrpy uses a 'log-normal' distribution to describe the fundamental frequency(f0) obtained by HVSR rather than a normal distribution. This increases its consistency in the ground motion processing of earthquakes and allows a seamless transition between HVSR states of both frequency and period [Cox et. al. - 2021].

2. To decrease variance and increase data quality, Hvsrpy uses a frequency-domain window-rejection algorithm, which essentially acts as a filter that removes outlier frequencies [Cox, B., et. al. - 2021]. This provides more consistent results even if the ambient noise wave field at the site has an anomaly.

3. Automatic checking of the SESAME (2004) criteria.

Part Ten

Studied Site Information

Site A: STORENGY (Trois-Fontaines-l'Abbaye, France)

Introduction

This site is maintained by Storengy, a French company that focuses on the storage of Natural Gas in the subsurface, and is located in France in three departments: Marne, Meuse, and Haute-Marne.

storengy

The storage perimeter covers 11 municipalities: Trois-Fontaines-l'Abbaye, Cheminon, Chancenay, Ancerville, Baudonvilliers, Bazincourt-sur-Saulx, Cousances-les-Forges, L'Isle-en-Rigault, Rupt-aux-Nonains, Saudrupt, and Sommelonne.

Figure 9: Location of Storengy Site Trois-Dountains-l'Abbaye [From storengy.fr]

Here, the Geological Storage of Natural Gas is carried out in an old depleted gas reservoir, which is at a depth of 1700 m from the surface. The reservoir has a height of approximately 4000 m and length of 17000 meters, which accounts for a total storage capacity of 80 million cubic meter.

The site was first built in the 1980s and was operated by COPAREX until 1994, after which the site was bought by Gaz de France and continued operations until 2006. The exploitation of the deposit was stopped in 2006, and 2,000 million cubic meter of gas was produced. The site was then adapted for conversion into an underground gas storage. In May 2010, Storeny was authorized to resume operation of the site and facilities. Storengy carried out final complete tests in 2022, and the site was restarted in 2023 as a natural-gas storage facility.

In order to keep the surrounding areas safe from seismic risk, Storengy studied the site's seismic activity in 2022, and installed 14 Seismic Stations equipped with 3-component seismometers with a corner frequency of 1 Hz, which records ambient noise and monitors sites for low microseismic activities 24/7.

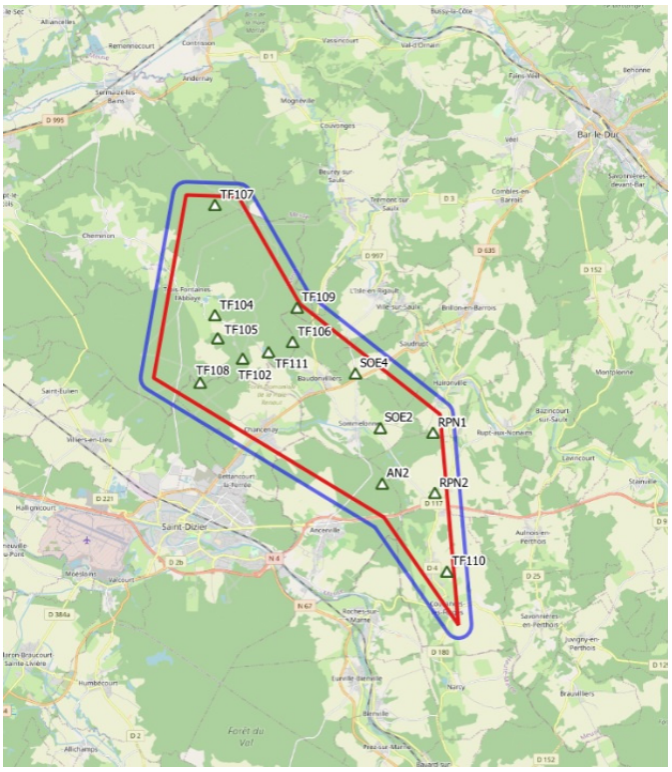


Figure 10: Location of Trois-Fountaines-l'Abbaye's 14 seismic stations]

Of the 14 seismic stations, we studied eight stations in

TFA:

1. RPN2
2. AN2
3. SOE2
4. SOE4
5. TF102
6. TF104
7. TF106
8. TF107

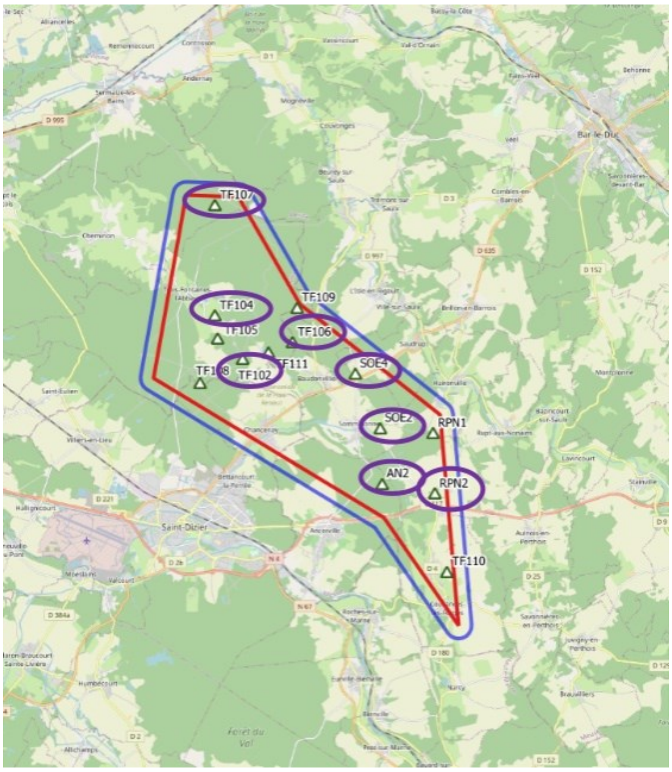


Figure 11: Location of Trois-Fountaines-l'Abbaye's 8 seismic stations that we studied]

Subsurface information

During the testing phase of the site in 2022, Vertical Seismic Profiling was performed. Figure 12 shows the result of this test:

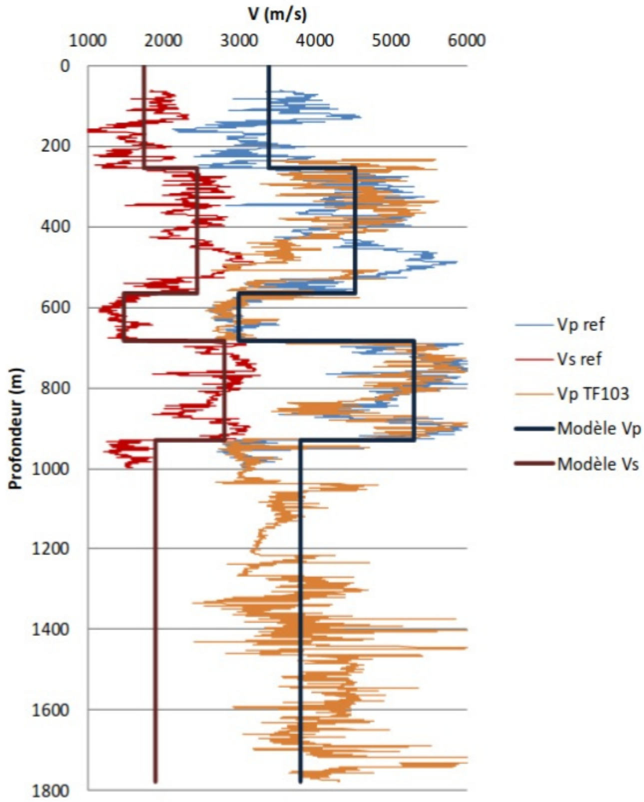


Figure 12: VSP at TFA

The Tests revealed a sudden jump in P-wave velocity from 3381 m/s to 4533 m/s, as well as in S-wave velocity from 1738 m/s to 2444 m/s, at a depth of 254 m.

Seismic Stations at Trois-Fontaines-l'Abbaye (TFA)

The Seismic Stations at TFA were deployed, during mid-2022, by a French company as a Third Party contract. However, owing to unclear data recorded, a physical intervention was needed, which was carried out on December 10, 2022, for seismic stations:

1. TF104
2. RPN2

On reaching the TF104 site, technicians found water inside the PE barrel in which the seismograph was placed. The Seismometer was found floating inside a barrel filled with water and was completely decoupled. In addition, the RPN2 was decoupled.

Both stations were fixed by technicians; however, station deployment was not carried out as per the SESAME guidelines [14]. This affected the data-collection capability of the stations. But, as the saying goes "Every Cloud has a Silver Lining," this intervention gave us a chance the check the efficiency of our method.

The intervention solutions and changes performed at both stations are as follows:

1. TF104:

The seismometer was replaced with another 1 Hz seismometer with an IPX2 water-repellent coating. Because IPX2 is not very resistant to water pressure, the barrel was placed slightly above the ground surface to ensure that there was no water seepage.

2. RPN2:

Placed inside a PE barrel filled with sand. To protect against wind, a barrel was placed below the ground surface. A considerable amount of weight was placed on the barrel to ensure a good coupling.

Figure 13: Seismometer Deployed at TFA

Figure 14: Station 104's seismometer holding barrel - filled with water due to seepage

Figure 15: Seismometer Deployed at TFA

Site B

Due to "Confidentiality" agreements signed between Isamgeo Italia S.r.l. and the company carrying out the operations in Site B, we cannot disclose much information on Site B and we will be referring this site as "Site B".

Information Available for the discloser:

- The site is being explored as a promising Geothermal Energy producing zone
- Nine seismic stations were installed with seismometers with a corner frequency of 1 Hz. The pseudonyms of the stations are as follows:

1. ST1
2. ST2
3. ST3
4. ST4
5. ST5
6. ST6
7. ST7
8. ST8
9. ST9

- Raw velocity log shows a jump in P-wave Velocity at the depth of approx 550 meters

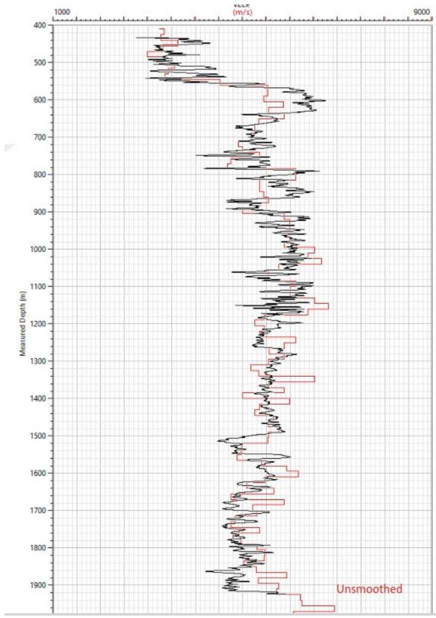


Figure 16: Raw Velocity Log at Site B

Part Eleven

Preliminary Application of HVSR with Geopsy & Results

Site Peak frequency ('fo')

Here, we took 24 h data from Site A to produce HVSR curves and obtain the Site Peak frequency. As mentioned earlier, the goal here is not to understand the site response but to check whether we are getting consistent values over time. The HVSR curves were produced station-by-station for four different dates, 1st May 2022, 3rd July 2022, September 25, 2022; and January 1, 2022, which fall on Sundays (to obtain the lowest anthropogenic noise). The gray line present on every curve represent the peak frequency 'f0.'

AN2

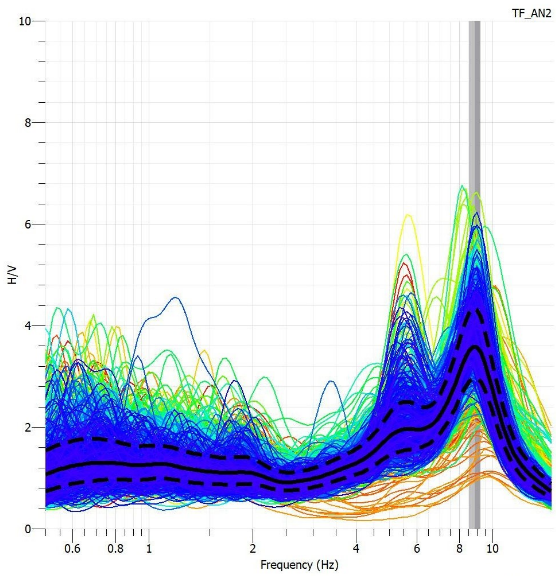


Figure 17: HVSR curves produced by Geopsy for the date 1st May 2022. Peak Frequency = 8.9 Hz

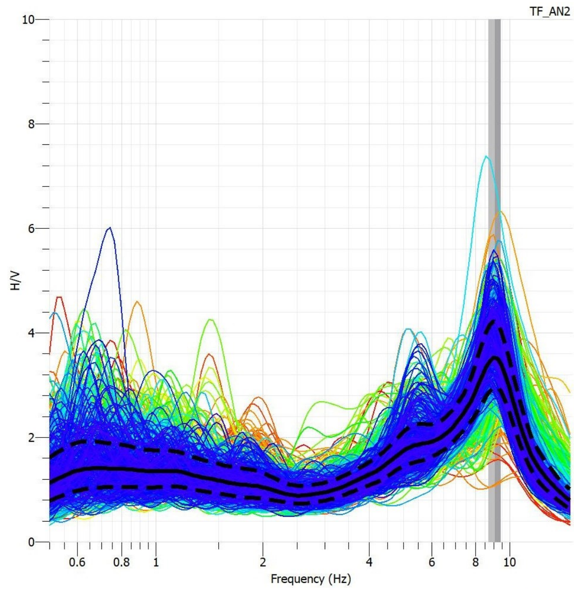


Figure 18: *HVSR curves produced by Geopsy for the date 3rd July 2022. Peak Frequency = 9 Hz*

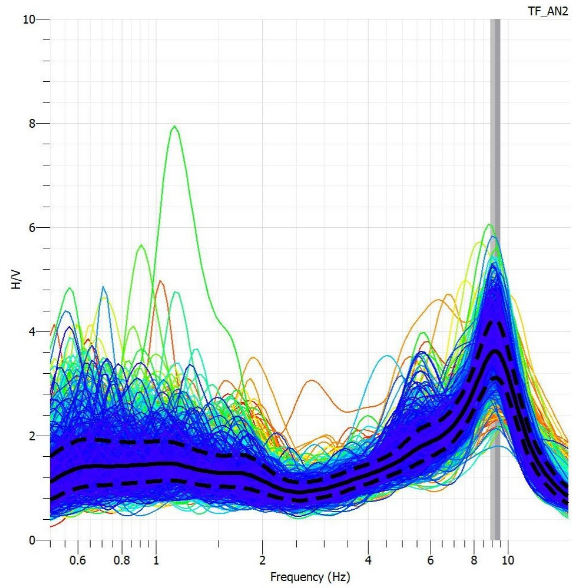


Figure 19: *HVSR curves produced by Geopsy for the date 25th September 2022. Peak Frequency = 9.1 Hz*

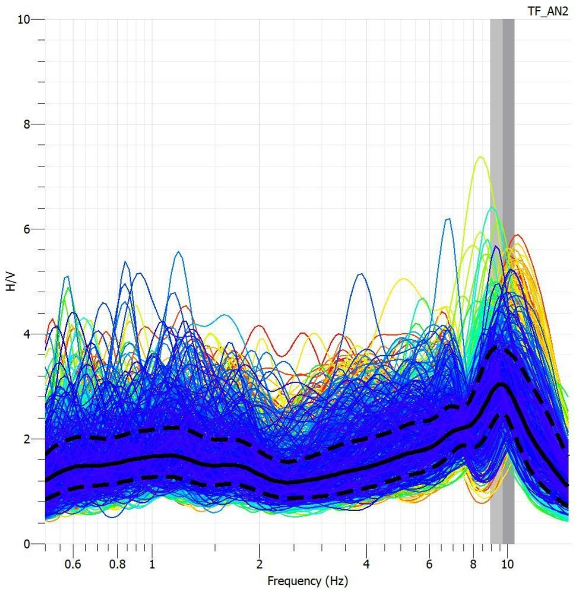


Figure 20: *HVSR curves produced by Geopsy for the date 1st January 2022. Peak Frequency = 9.1 Hz*

TF102

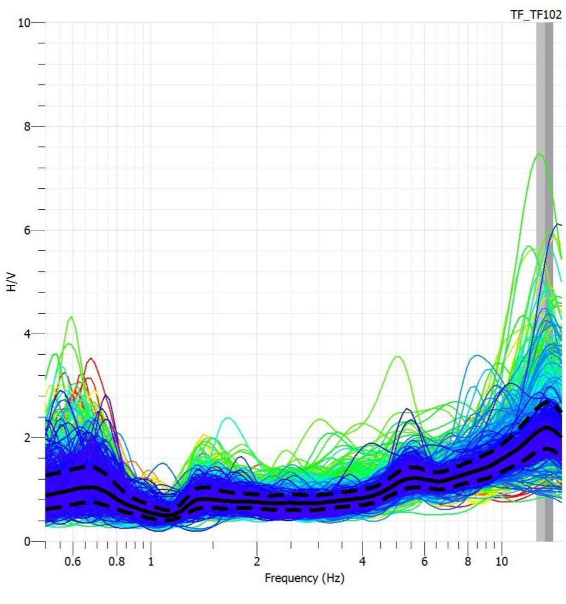


Figure 21: HVSR curves produced by Geopsy for the date 1st May 2022. Peak Frequency = 13 Hz

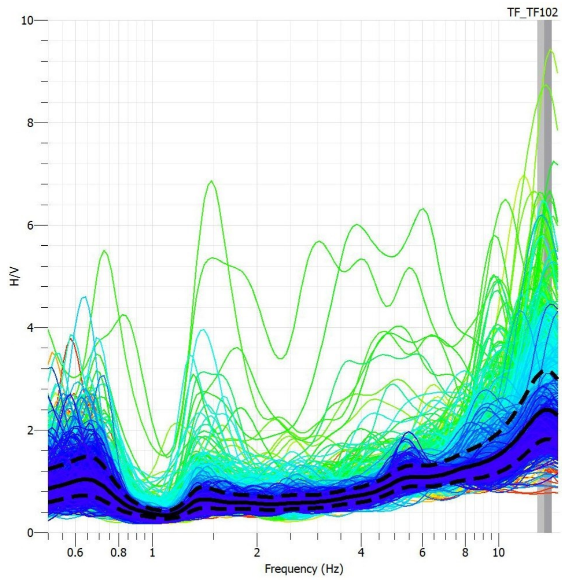


Figure 22: HVSR curves produced by Geopsy for the date 3rd July 2022. Peak Frequency = 13.2 Hz

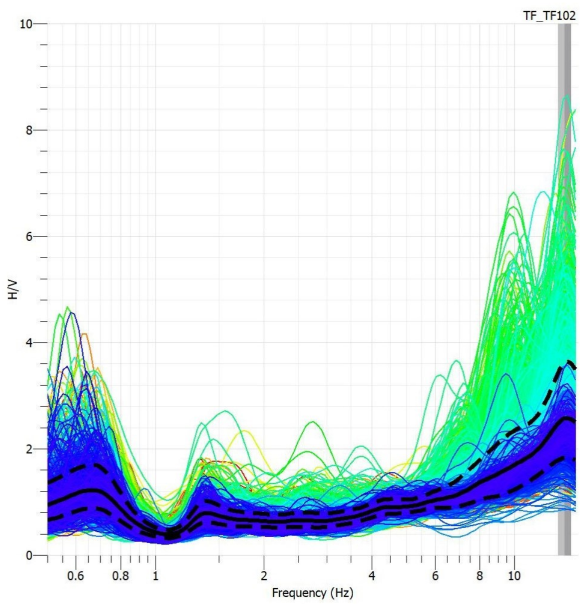


Figure 23: HVSR curves produced by Geopsy for the date 25th September 2022. Peak Frequency = 13 Hz

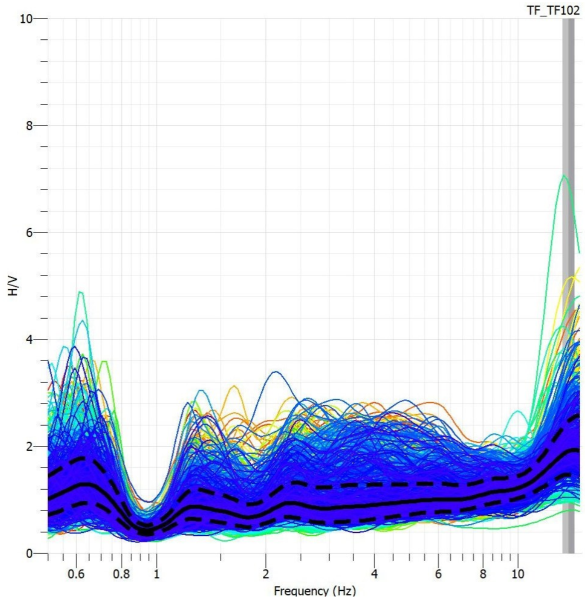


Figure 24: HVSR curves produced by Geopsy for the date 1st January 2022. Peak Frequency = 13 Hz

SOE2

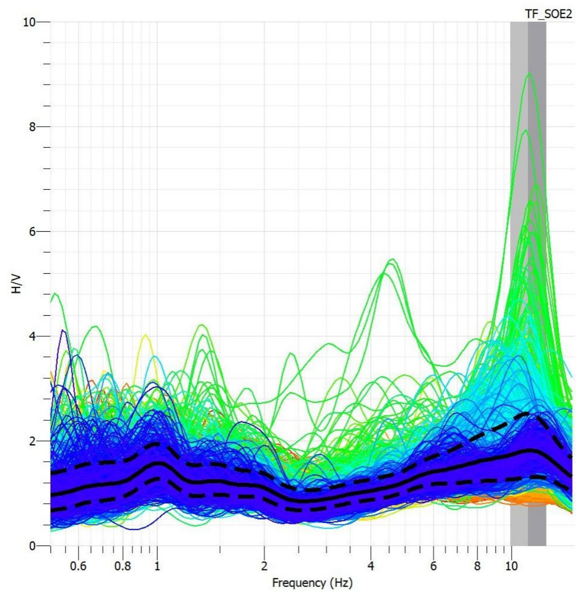


Figure 25: HVSR curves produced by Geopsy for the date 1st May 2022. Peak Frequency = 11.5 Hz

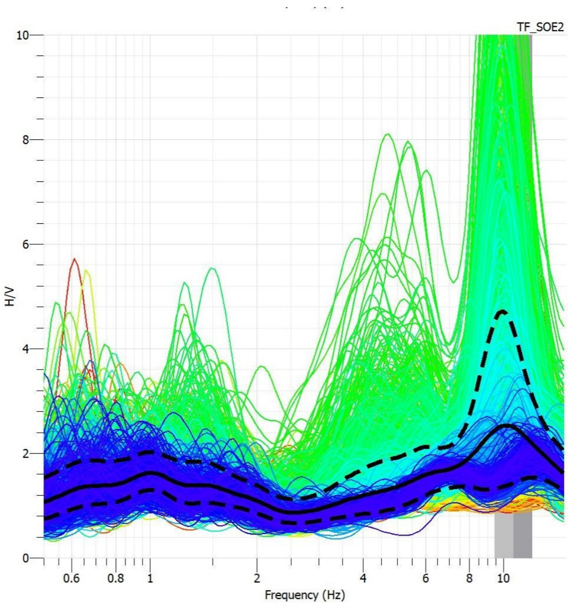


Figure 26: HVSR curves produced by Geopsy for the date 3rd July 2022. Peak Frequency = 10.8 Hz

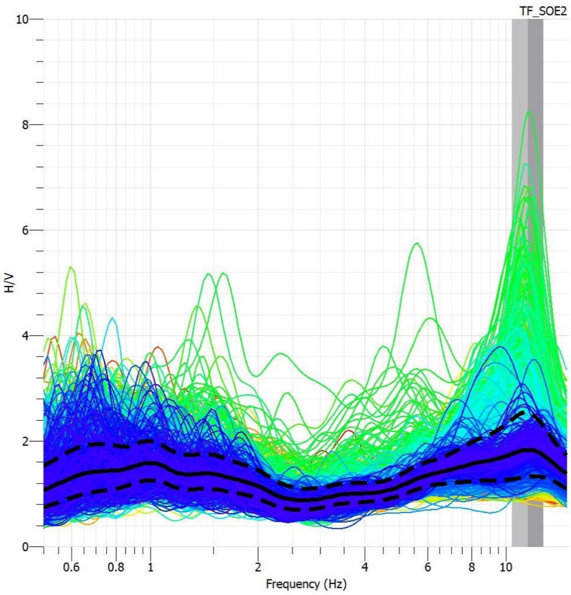


Figure 27: HVSR curves produced by Geopsy for the date 25th September 2022. Peak Frequency = 11.2 Hz

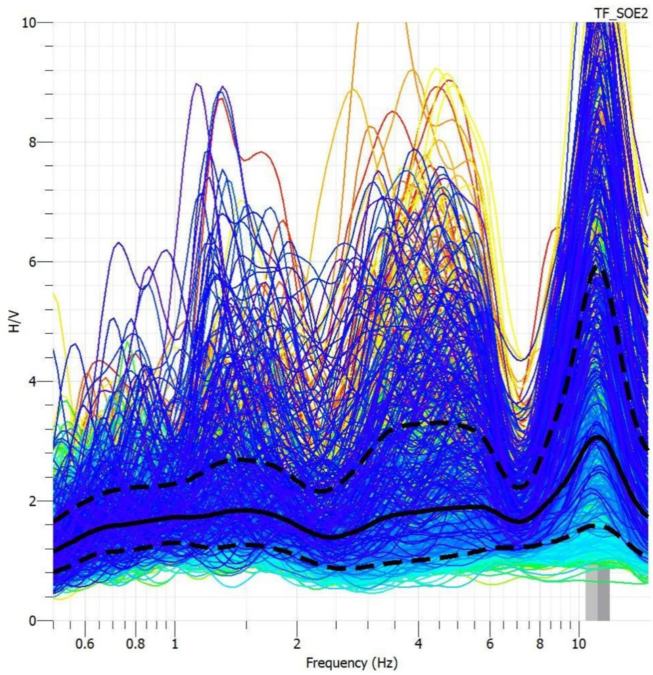


Figure 28: HVSR curves produced by Geopsy for the date 1st January 2022. Peak Frequency = 11.1 Hz

TF107

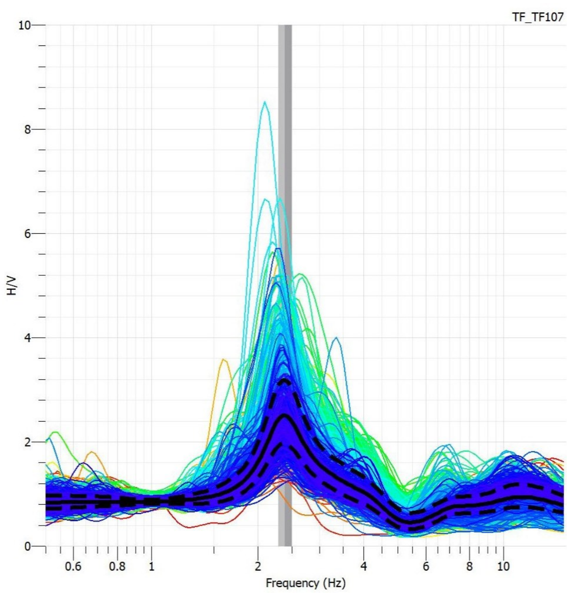


Figure 29: HVSR curves produced by Geopsy for the date 1st May 2022. Peak Frequency = 2.4 Hz

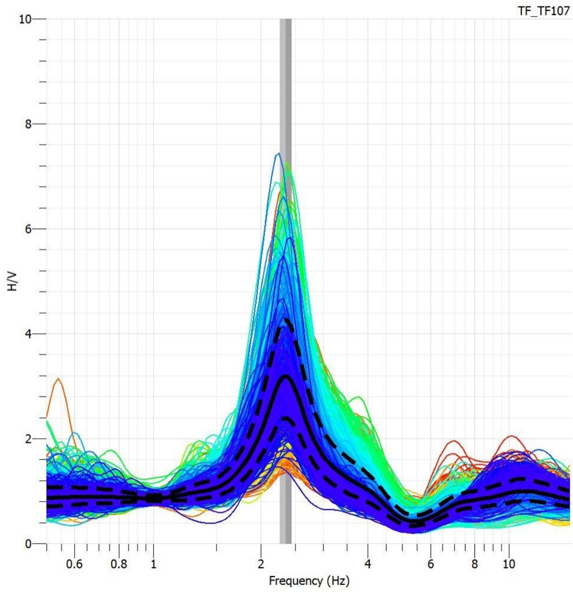


Figure 30: HVSR curves produced by Geopsy for the date 3rd July 2022. Peak Frequency = 2.4 Hz

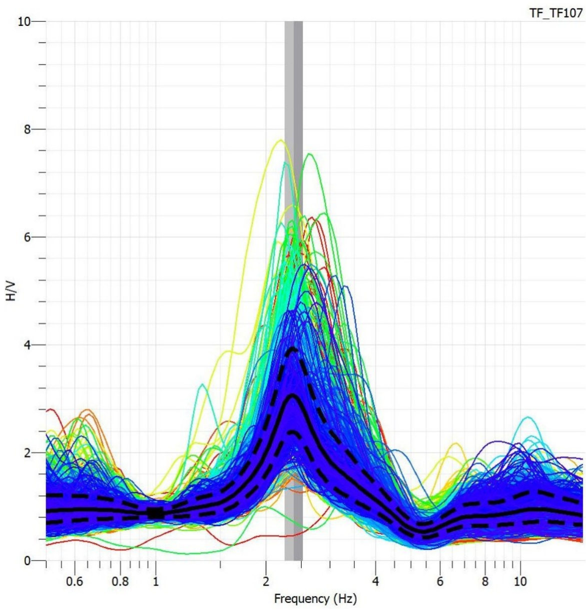


Figure 31: HVSR curves produced by Geopsy for the date 25th September 2022. Peak Frequency = 2.4 Hz

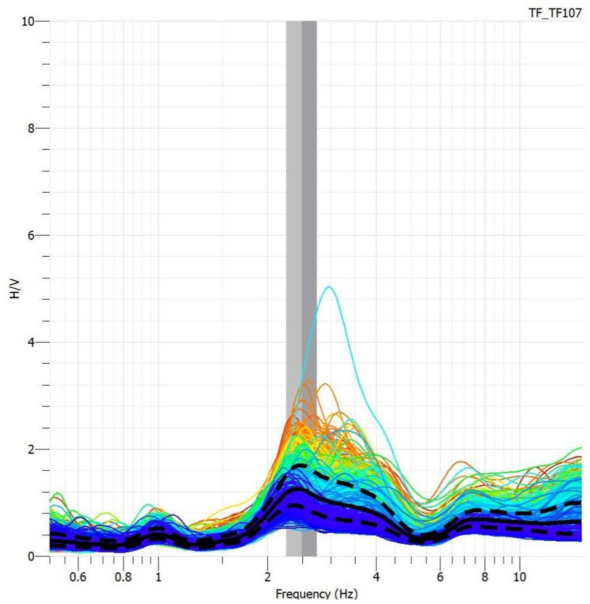


Figure 32: HVSR curves produced by Geopsy for the date 1st January 2022. Peak Frequency = 2.5 Hz

Thus, as we can tell from the results, even over the span of nine months, the peak frequency values are quite consistent. Hence, we can conclude that the HVSR peak frequency value remains consistent over time at a given location.

Data Duration and HVSR

For the calculation of peak frequency we used 24 hour data; however, we wanted to check the consistency of the method even if we had a smaller range of data. Thus, the HVSR curves were produced by 24 h of data and 2 h of data. For the 2 hour data, we considered the data recorded between 2 and 4 Am, when the human-induced noise was the lowest [Nakamura, Y., - 1989].

AN2

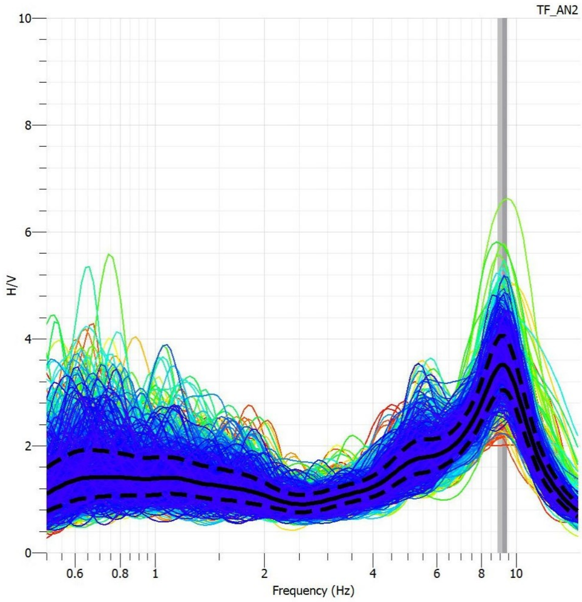


Figure 33: *HVSR curves produced by Geopsy for the date 28th August 2022 with 24 hours data. Peak Frequency = 9.6 Hz*

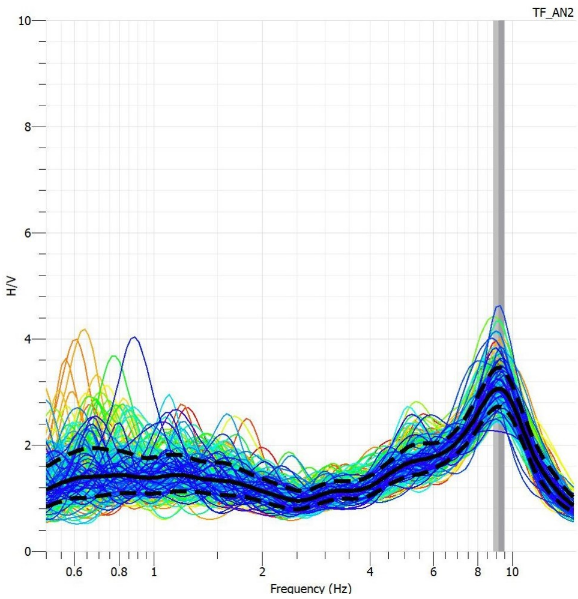


Figure 34: *HVSR curves produced by Geopsy for the date 28th August 2022 with 2 hours data. Peak Frequency = 9.6 Hz*

TF102

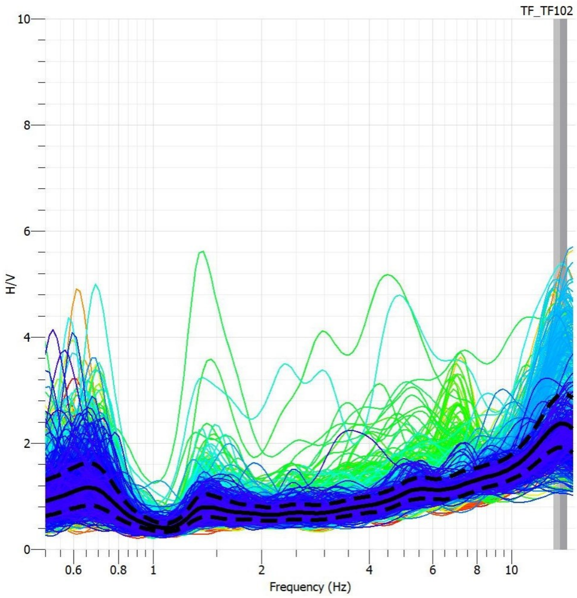


Figure 35: *HVSR curves produced by Geopsy for the date 28th August 2022 with 24 hours data. Peak Frequency = 13 Hz*

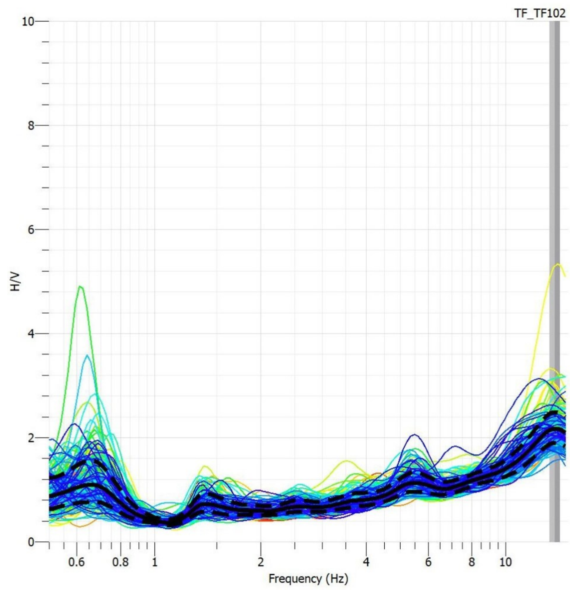


Figure 36: HVSR curves produced by Geopsy for the date 28th August 2022 with 2 hours data. Peak Frequency = 13 Hz

TF106

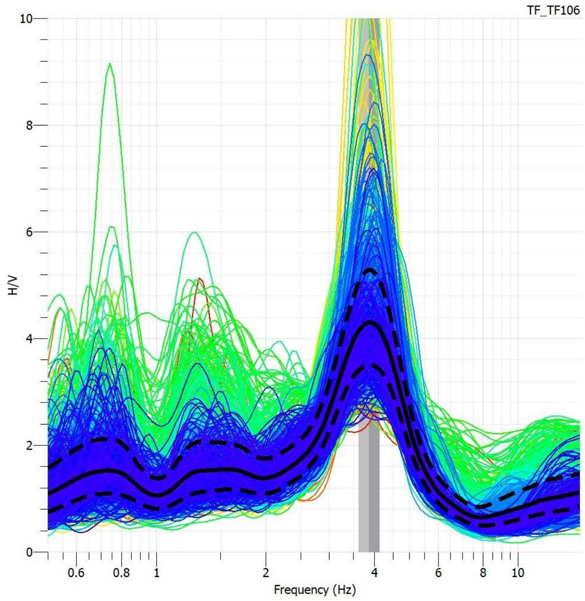


Figure 37: *HVSR curves produced by Geopsy for the date 28th August 2022 with 24 hours data. Peak Frequency = 3.8 Hz*

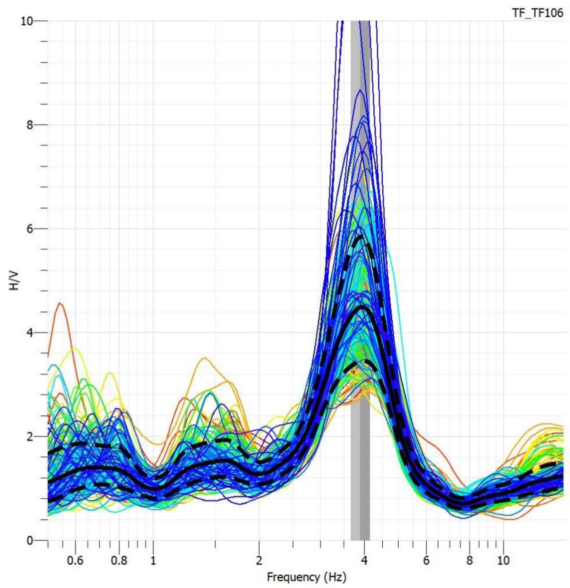


Figure 38: *HVSR curves produced by Geopsy for the date 28th August 2022 with 2 hours data. Peak Frequency = 3.7 Hz*

Hence, we can conclude from the results that the HVSR curve produces similar results even when the data duration does not have a significant impact on the results.

Comparing PPSD curves with HVSR curves

RPN2

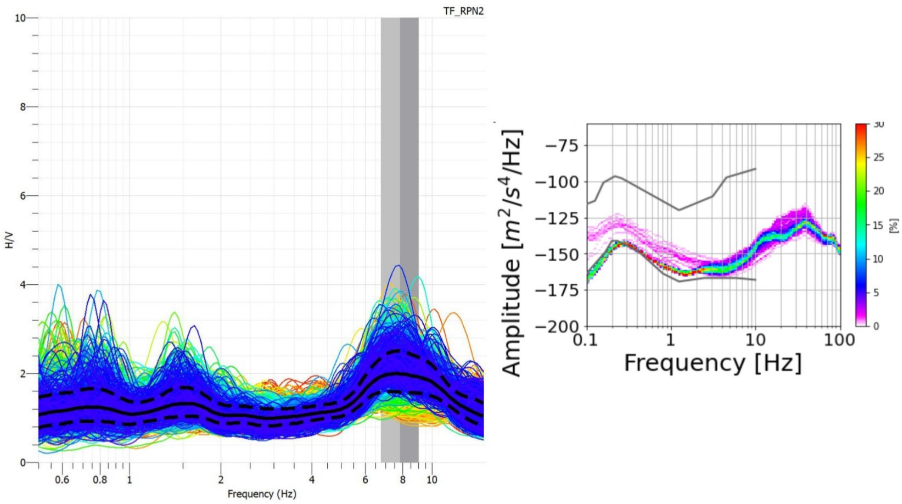


Figure 39: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 4th December 2022

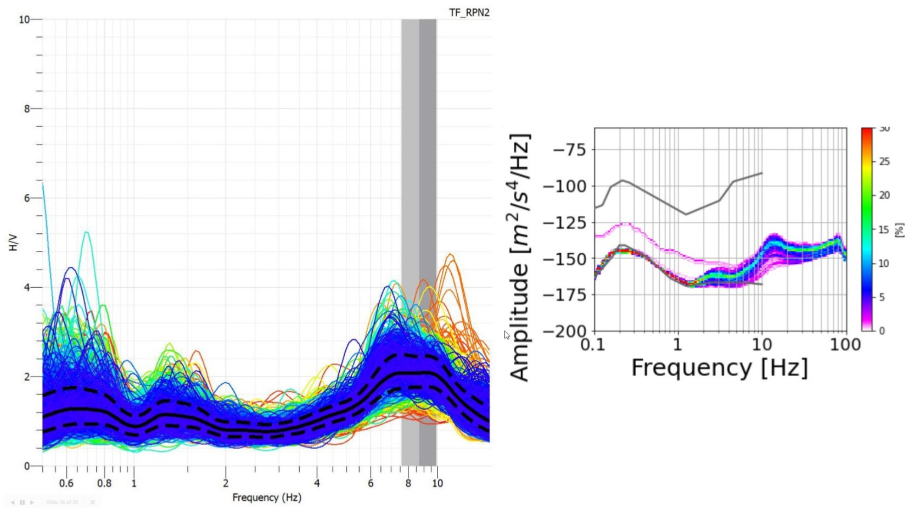


Figure 40: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 11th December 2022

For RPN2, the PPSD curves, on 4th December, shows a bit of noise; however, the peak frequency produced by HVSR on 4th December is approx 7.6 Hz. After maintenance intervention, the peak frequency was 8.6 Hz.

TF104

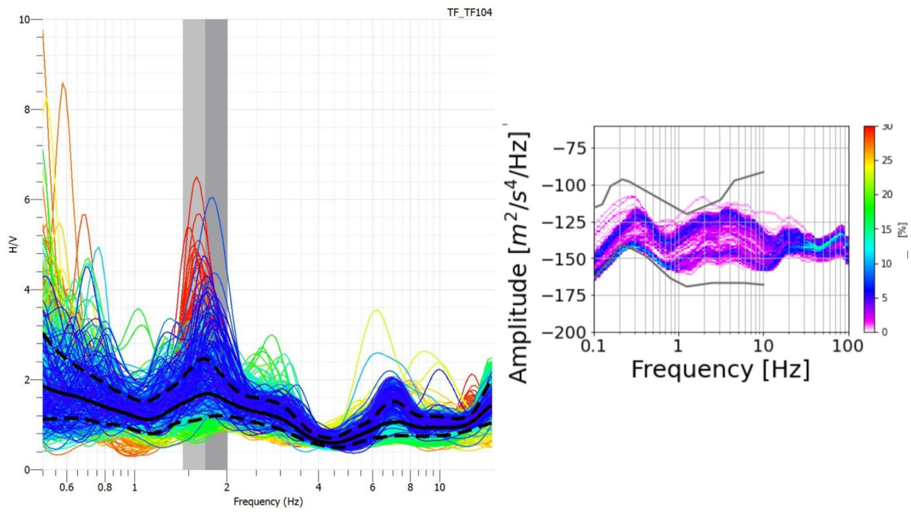


Figure 41: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 4th December 2022

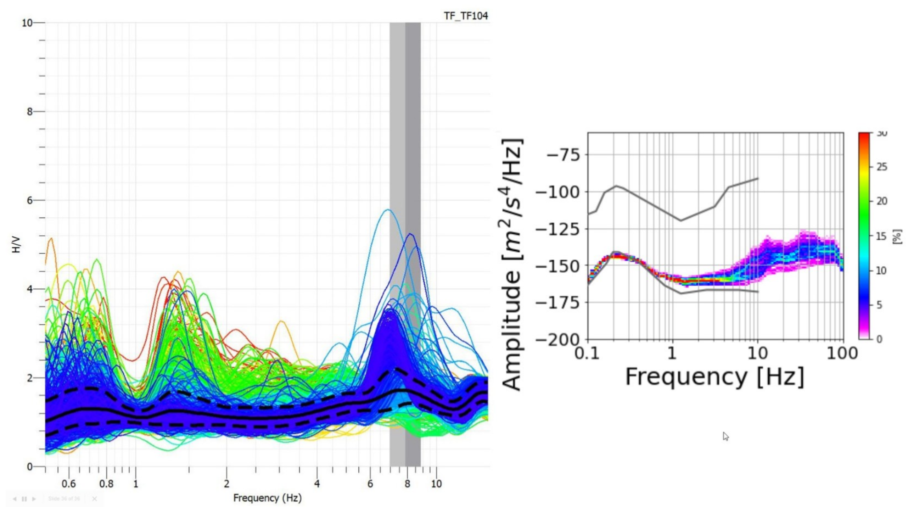


Figure 42: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 11th December 2022

For TF104, which was completely decoupled on 4th December, the PPSD curves showed very noisy data; the peak frequency produced by the HVSR on 4th December is approx 1.7 Hz. After maintenance intervention, the peak frequency was 8 Hz.

AN2

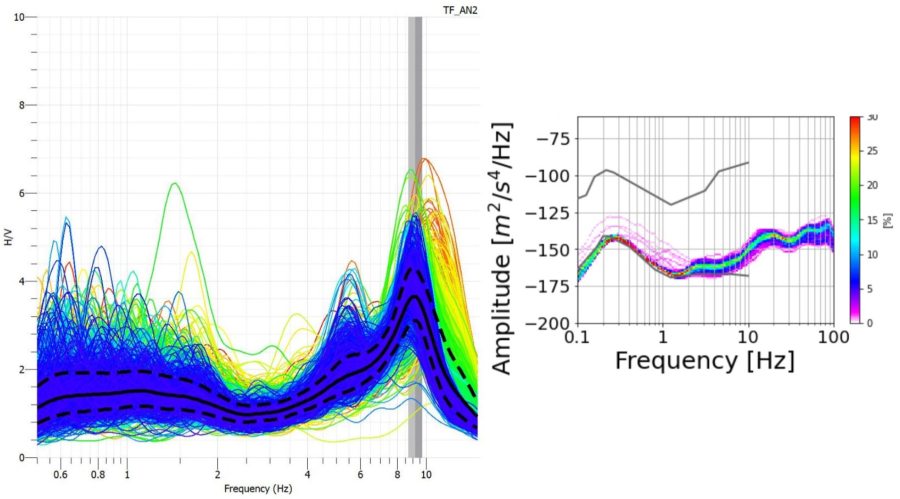


Figure 43: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 4th December 2022

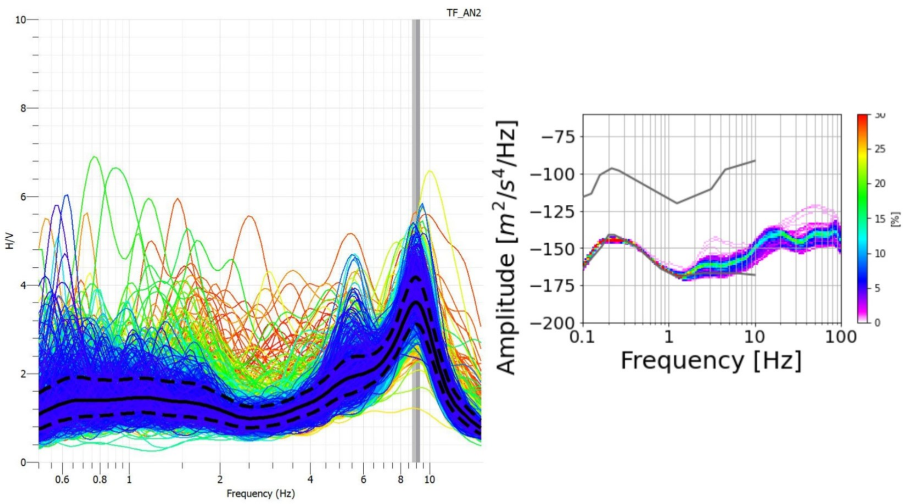


Figure 44: HVSR curves produced by Geopsy (Left) & PPSD produced (Right) for the date 11th December 2022

For AN2, which is one of the most stable stations at Site A, the PPSD curves, on 4th December, shows a bit of noise; however, the Peak Frequency produced by HVSR on 4th December is approx 9.1 Hz which is the same as its average peak frequency of 9 Hz.

From the aforementioned results, we can appreciate and conclude the effectiveness of the HVSR peak frequency for quality control. The results are not consistent with the PPSD results and the site information that we have, but also gave us a metrice in the form of Peak Frequency f0 that we can use to estimate the health of the network.

Part Twelve

Comparing Geopsy with hvsrpy Python Package

We compared the software "Geopsy" with the python Package "hvsrpy" taking the 24 hours data from Site A, at Trois-Fontaines-l'Abbaye, for dates:

1. 4th December 2022
2. 11th December 2022

To obtain a comparative analysis of how the software and package were performed before and after the site maintenance intervention was performed on December 10, 2022.

The dates December 4, 2022, and December 11, 2022, were chosen because they both fall on Sundays, when the Anthropogenic noise is the lowest due to holidays.

We also applied different filters and smoothing functions for comparative analysis. SESAME recommends Konno-Ohmachi smoothing of 40% for the H/V spectral ratio[14].

RPN2

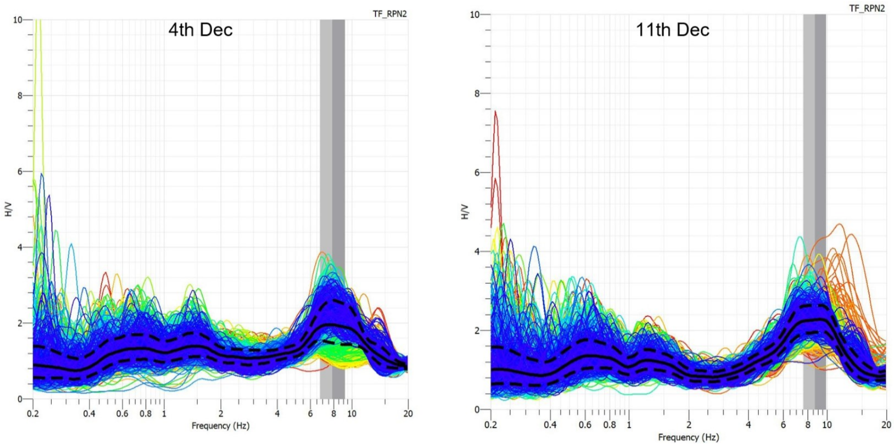


Figure 45: HVSR curves produced by Geopsy for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 40%

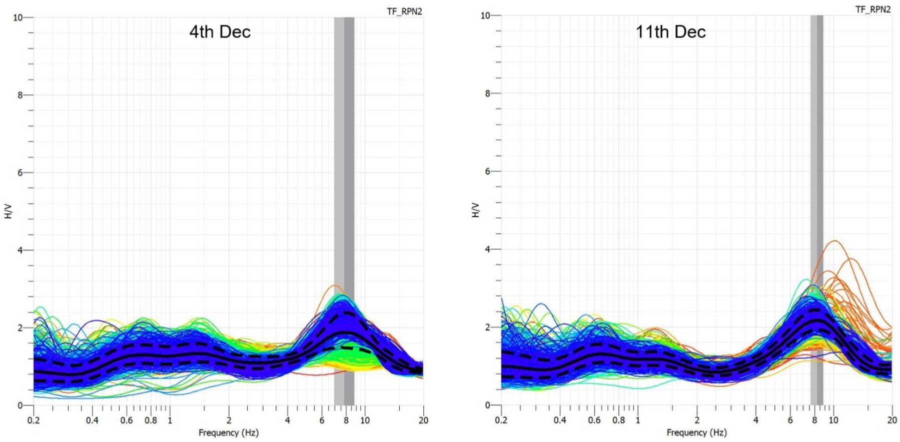


Figure 46: HVSR curves produced by Geopsy for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 99.99%

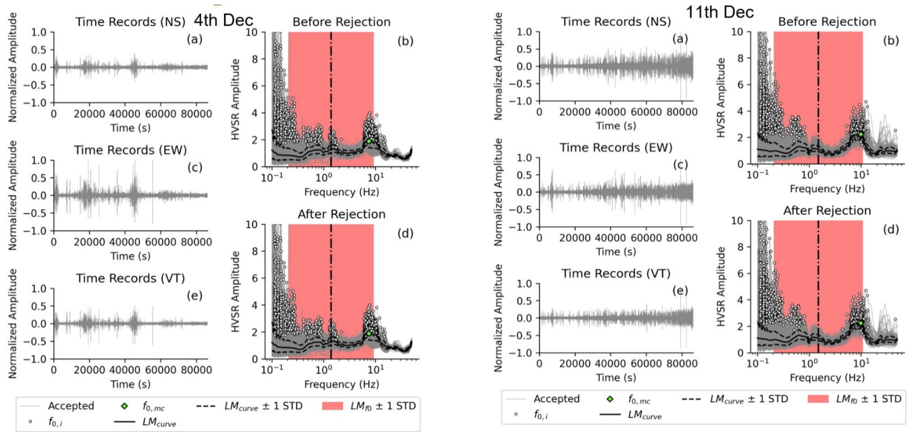


Figure 47: HVSR curves produced by hvsrpy Python Package for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 40%

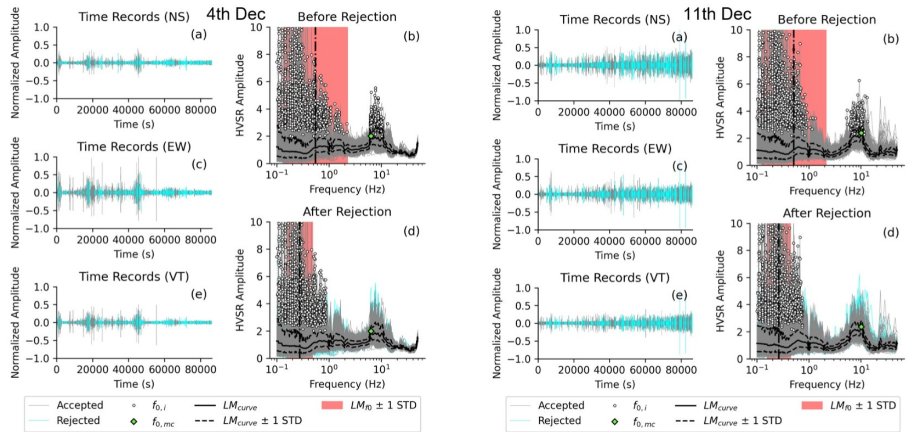


Figure 48: HVSR curves produced by hvsrpy Python Package for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 99.99%

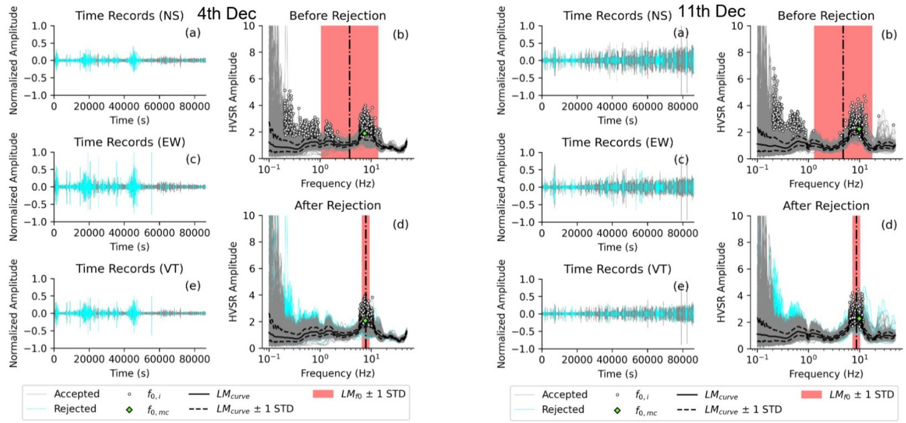


Figure 49: HVSR curves produced by hvsrpy Python Package for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 99.99%
High-pass Filter: 0.2 Hz

TF104

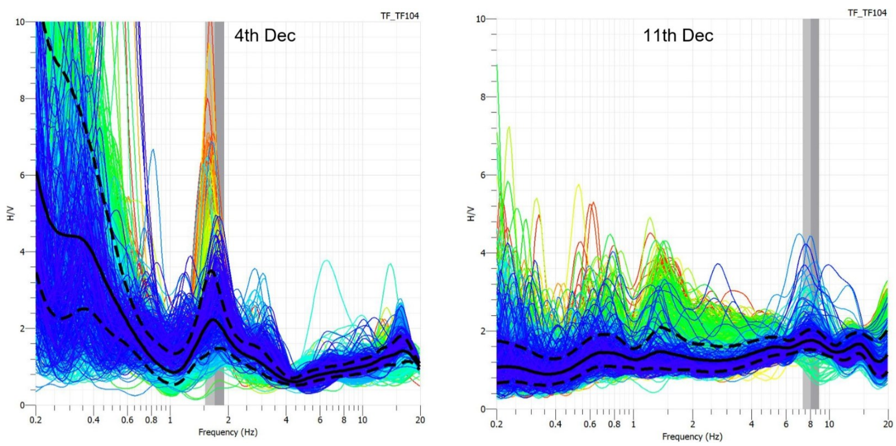


Figure 50: HVSR curves produced by Geopsy for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 40%

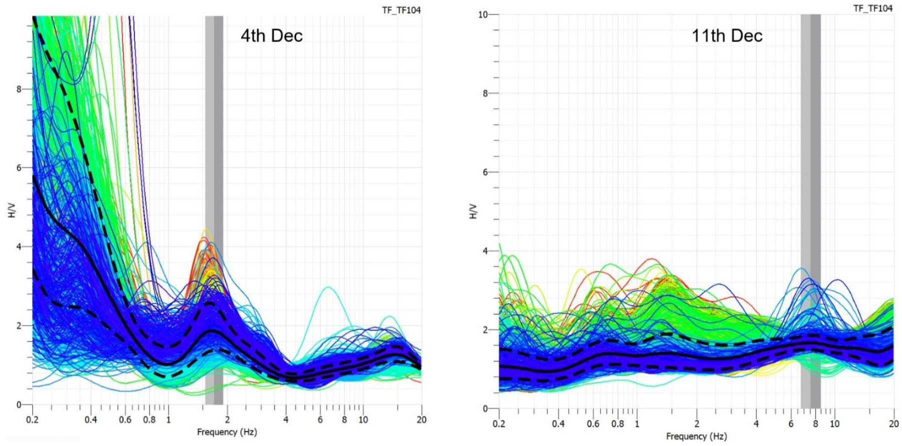


Figure 51: HVSR curves produced by Geopsy for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 99.99%

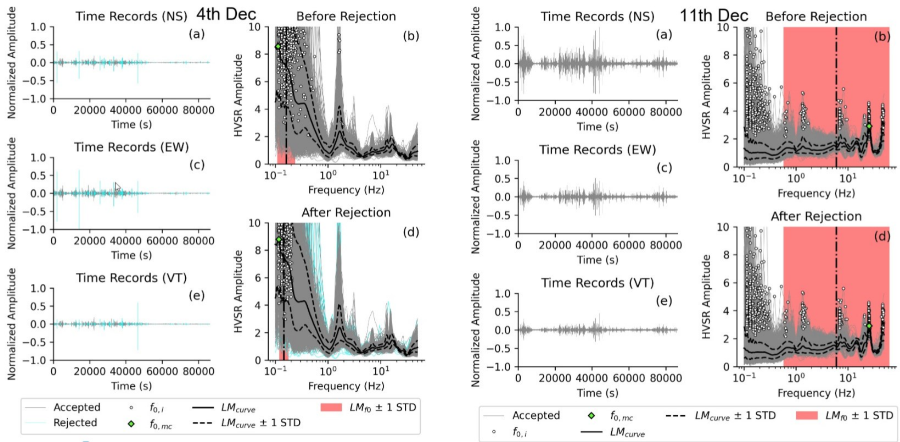


Figure 52: HVSR curves produced by hvsrpy Python Package for the dates 4th December 2022 (left) and 11th December 2022 (right)
Konno-Ohmachi Smoothing: 40%

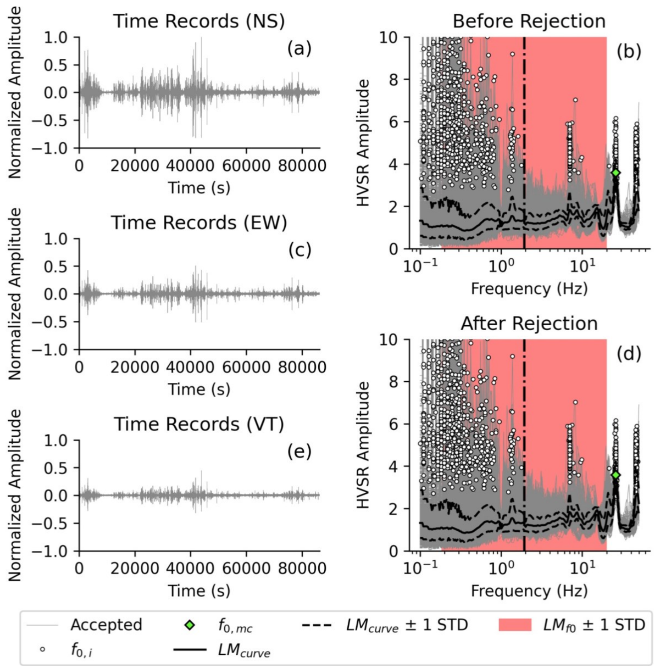


Figure 53: HVSR curves produced by hvsrpy Python Package for the date 11th December 2022

Konno-Ohmachi Smoothing: 99.99%

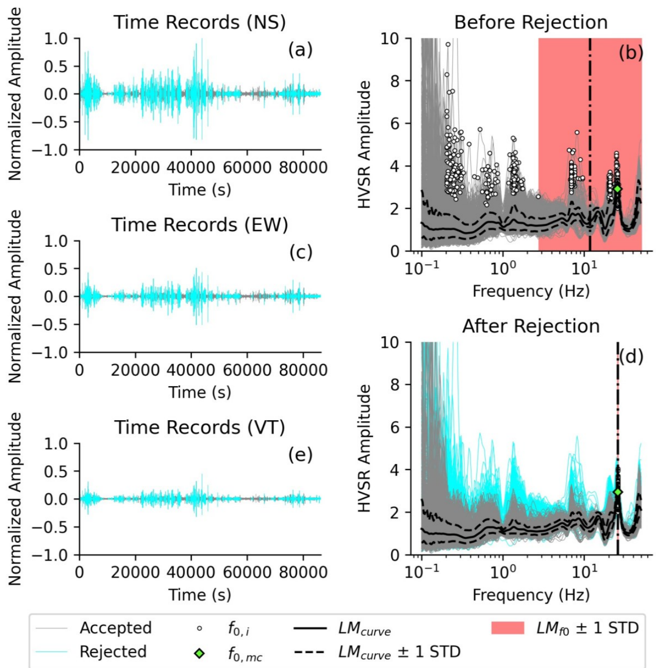


Figure 54: HVSR curves produced by hvsrpy Python Package for the date 11th December 2022

Konno-Ohmachi Smoothing: 99.99%

Bandpass Filter: 0.2 Hz - 30 Hz

Observations & Conclusions

- Geopsy: We obtained consistent results for both the RPN2 and TF104 stations, with a peak frequency of approximately 8 Hz. Application of the 99.99% Konno-Ohmachi filter did not significantly affect the results.
- hvsrpy Python Package: The Fundamental Frequency was lower than that of Geopsy because the algorithm picks up f0 at low frequencies owing to the high HVSR amplitude. A High HVSR amplitude may be an effect of the damping. Furthermore, the package was not able to generate HVSR curves for the 4th December data when KO smoothing of 99.99% was applied, but also when a bandpass filter was applied.
- From these observations, we can conclude that Geopsy has higher stability and consistency than the hvsrpy package.

Part Thirteen

Comparing Geopsy with hvsrpy Python Package

Various attempts have been made to use data collected from a Single Seismic Station to estimate the directionality of Ambient Noise waves or earthquakes. Hobinger, M., et. al. (2008) single station cross correlation technique; Darbyshire, J. (1954) uses phase difference between Horizontal and Vertical Components and theoretical values of Rayleigh waves to estimate direction; using vector particle motion records at single station etc. However, most of these studies have not been fruitful or complicated. With an array of sensors or a network of sensors, estimating the directionality of the incident wave using the triangulation method is relatively simple. However, in recent years, the development of the direction of the horizontal-to-vertical Spectral Ratio has shown some promise for single seismic stations.

The traditional horizontal-to-vertical spectral ratio is the ratio between the Fourier Amplitude spectra of the Horizontal Component, Geometric or root mean square average of the north-south and east-west directions [Cox, B., et. al. - 2021], of the seismometer to its Vertical Component; however, a Directional Horizontal to Vertical spectral Ratio or DHVSR calculates the spectral ratios for multiple horizontal directions, providing a set of directional spectral curves. It considers the anisotropy of the subsurface and can help identify the directional variability of seismic site effects. The effects of Subsurface were also studied in SESAME, where it was observed that the site has significant effects on the directionality of seismic noise that sensors capture; for instance, if the sensor is near a mountain, or if the sensor is on a basin, it affects the ambient noise characterization of the sensor due to local site effects [14]. The actual directionality of the ambient noise wave field may be completely different from that measured by DHVSR.

However, the low reliability of DHVSR does not affect us much, as our goal is not to directly understand the directionality of the ambient noise wave field, but to use the data collected as a means to perform quality control on our seismometers.

hvsrpy considering Azimuthal Variability

The hvsrpy Python package developed by Joseph P. Vantassel also has a dedicated function that calculates the DHVSR or HVSR using azimuthal variability. This package used the method developed by Cheng et al.. al. (2020) as a base for computation of f0 values.

Considering this, there are three methods for computing HVSR:

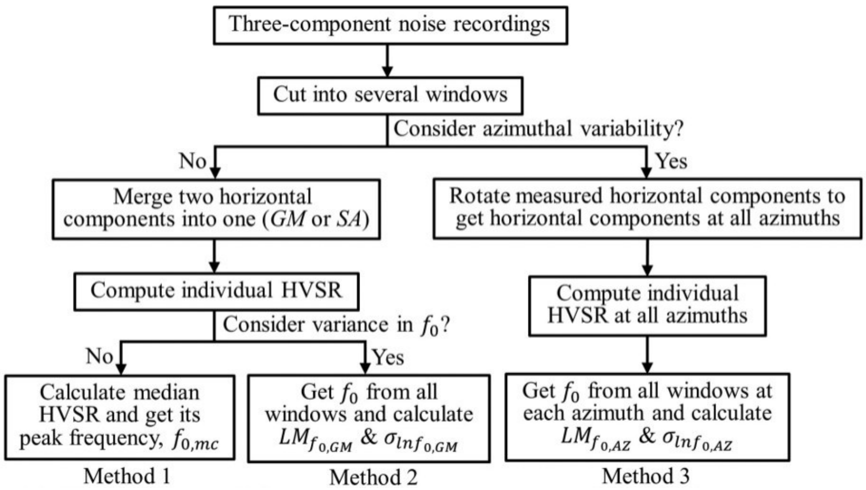


Figure 55: Showing the 3 Methods for the computation of HVSR [Diagram from: Cheng, T., et. al. - 2020]

Method 1: Belongs to Brad & SESAME team (2004) and the method used by the software geopsy.

Method 2: This method was developed by Cox et al.. al. (2021), and uses 'log-normal' distribution to describe fundamental frequency(f0) obtained by HVSR rather than using the normal distribution. This method uses hvsrpy and has a frequency-domain window rejection algorithm for consistent f0 values.

Method 3: Developed by Cheng et. al. (2020) also used by hvsrpy, considers azimuthal variability and produces DHVSR curves. In this approach, the azimuthal variations in the HVSR data can be investigated by studying the HVSR curves as a function of the azimuth. This process begins by rotating/ combining two horizontally measured objects (northwest-east-west) to obtain the horizontal time series representing any other arbitrary azimuth.

Assuming that north-south corresponds to 0∘ azimuth and α is the measured clockwise angle from the NS to the desired azimuth, then the horizontal component of azimuth α is calculated using the following equation in the time domain is calculated

HCα = HCNS*cos α + HCEW*sinα

Where, HCNS and HCEW are the concentrations in the NS and EW directions, respectively. When the horizontal section is obtained at azimuth α, it is used to obtain the HVSR by calculating its ratio with the vertical section. Then, f0 and amplitude are obtained. [Cheng, T., et. al. - 2020]

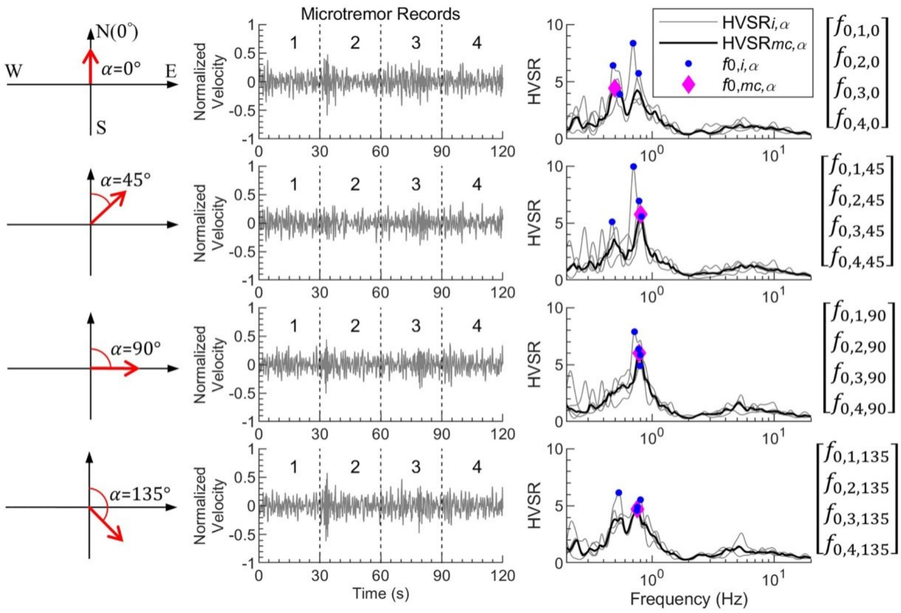


Figure 56: *Illustrating how HVSR curves at different azimuths α are calculated from the measured NS and EW horizontal components. In this example, four time windows and four azimuths (0∘,45∘, 90∘, 135∘) are considered [Diagram from: Cheng, T., et. al. - 2020]*

Part Fourteen

DHVSR, while using hvsrpy Azimuthal Variability Python Package

While using the hvsrpy Azimuthal variability package, graphs such as those shown in Figure 57 were produced.

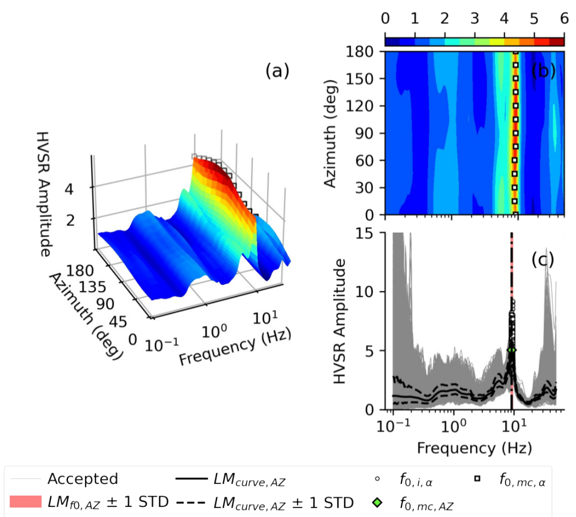


Figure 57: Station AN2 (Site A) produced by hvsrpy Azimuthal Package, with minimum frequency of 0.1 Hz, calculated with 24 hours of data (3rd January 2023)

In the three subplots, plot (c) is the normal HVSR curve; however, plots (a) and (b) show the peak frequencies at different azimuths. The script also produced a text file with data for each curve in which we could obtain the median peak frequency.

Effect of Data Duration on DHVSR

To check the effects of Data Duration on DHVSR, we generated DHVSR plots for four different durations: (a) 10 min, from 2:00 Am to 2:10 Am; (b)30 min, from 2:00 Am to 2:30 Am; (c)2 h, from 2:00 am to 4 am; and (d)24 h. The results are as follows.

Site A

Figure 58 shows the f0 values for station AN2 over time. In an ideal case, all points should be in a single line and overlaid with each other. However, even though the results are not ideal, we can see that the points or f0 values produced by different data lengths follow the same high and low patters, as well as cloud together, this is most evident in the plot, for data between 5th Feb 2023 to 28th March 2023, when f0 values suddenly plummeted for all the time durations

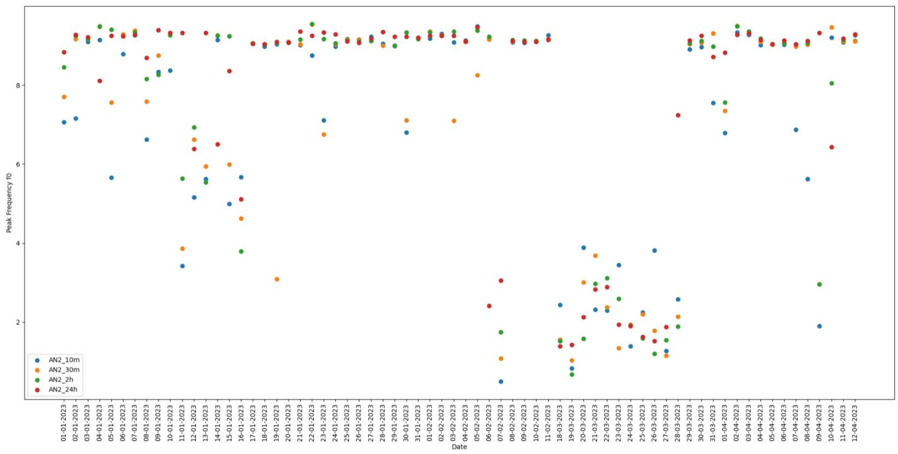


Figure 58: Site A f0 Values, for station AN2 over time with minimum frequency of 0.1 Hz. Values were calculated with 4 different lengths of data: 10 minutes (2:00 Am to 2:10 Am), 30 minutes (2:00 Am to 2:30 Am), 2 hours (2:00 Am to 4 Am) and 24 hours.

In addition, from the following Figures, we can see the Azimuth remaining constant, despite the change in Data Duration, for Station AN2:

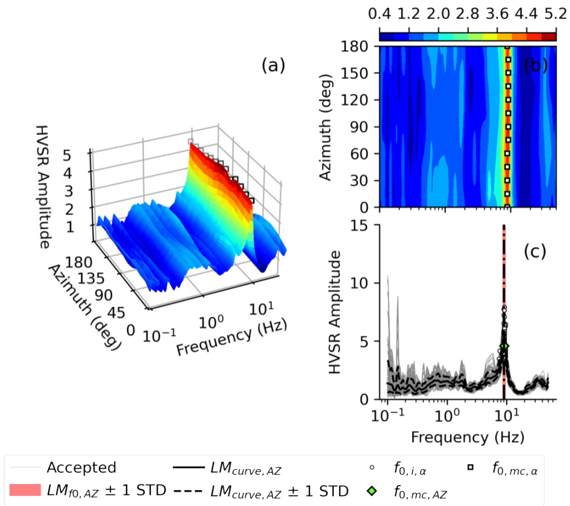


Figure 59: AN2 January 03, 2023; Data Duration: 10 mins

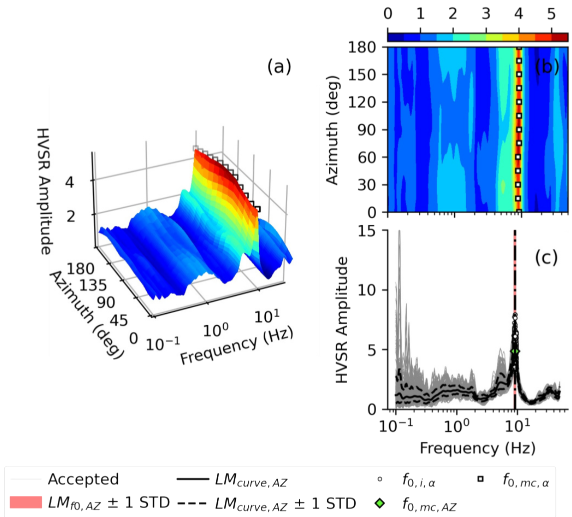


Figure 60: AN2 January 03, 2023; Data Duration: 30 mins

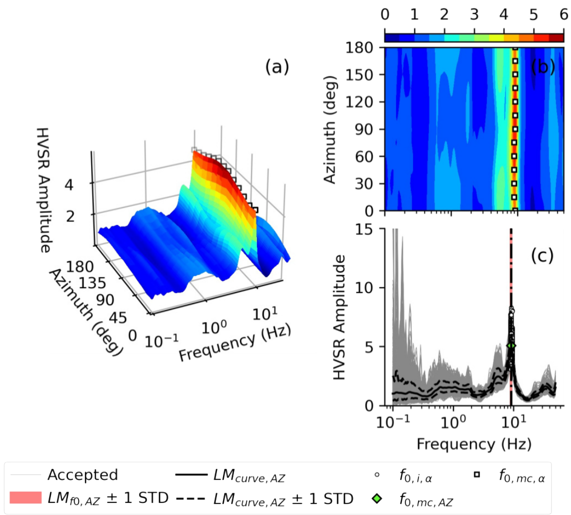


Figure 61: AN2 January 03, 2023; Data Duration: 2 hours

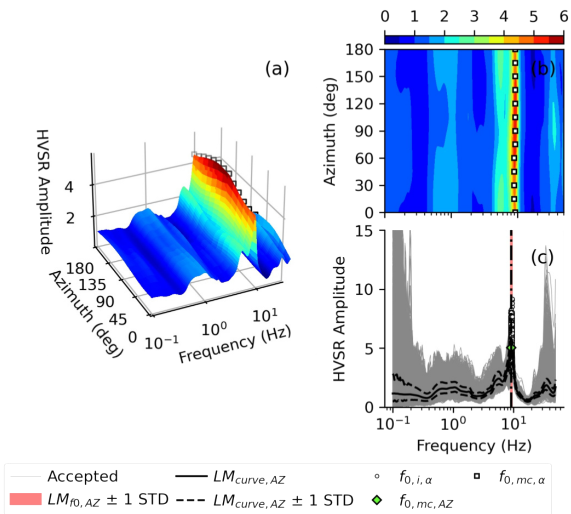


Figure 62: AN2 January 03, 2023; Data Duration: 24 hours

Site B

Similar to Site A, as shown in Figure 63, for Site B, the f0 values obtained from different data durations seem to be grouped together and follow a similar trend.

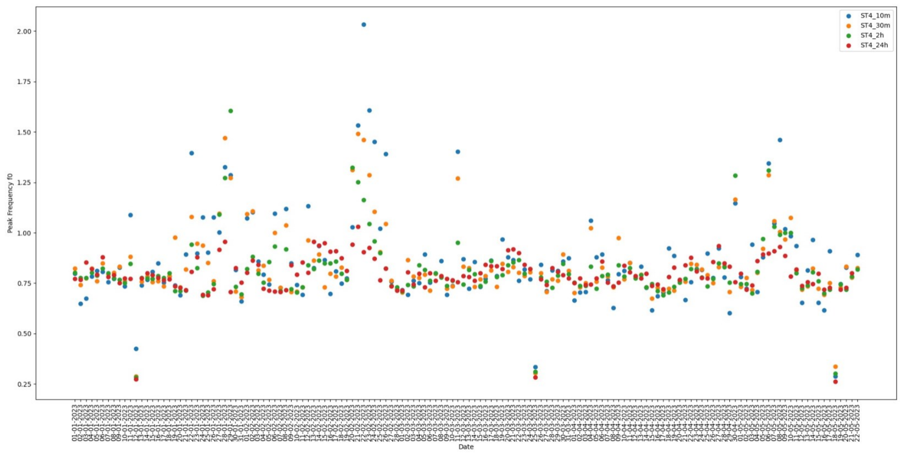


Figure 63: Site B f0 Values, for station ST4 over time with minimum frequency of 0.1 Hz. Values were calculated with 4 different lengths of data: 10 minutes (2:00 Am to 2:10 Am), 30 minutes (2:00 Am to 2:30 Am), 2 hours (2:00 Am to 4 Am) and 24 hours.

Similar to Site A from the following Figures, we can see the Azimuth remaining constant, despite the change in Data Duration, for Station ST4.

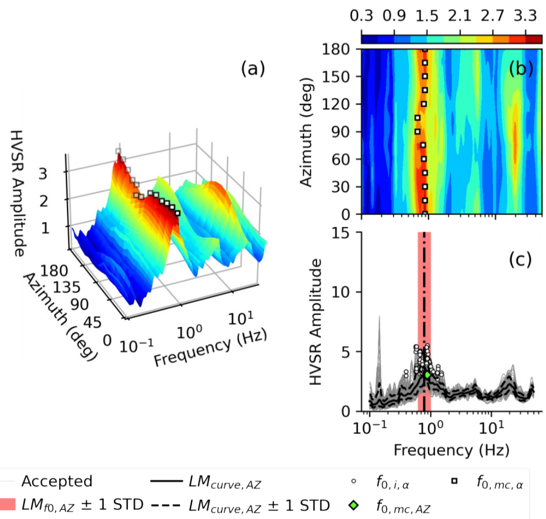


Figure 64: ST4 January 01, 2023; Data Duration: 10 mins

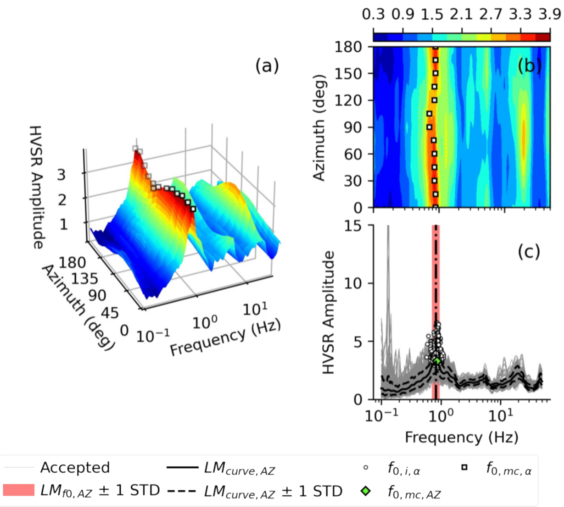


Figure 65: ST4 January 01, 2023; Data Duration: 30 mins

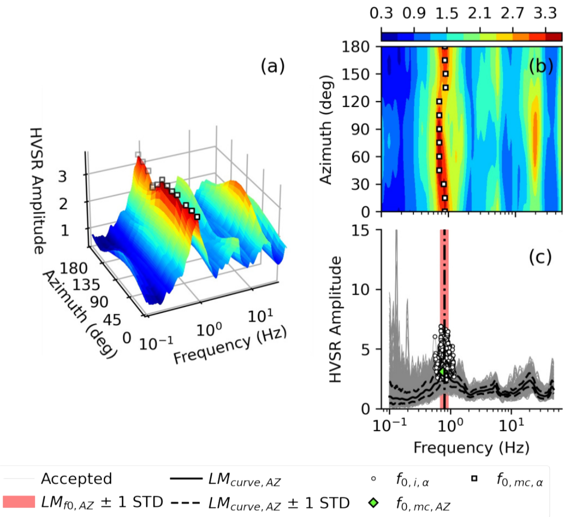


Figure 66: ST4 January 01, 2023; Data Duration: 2 hours

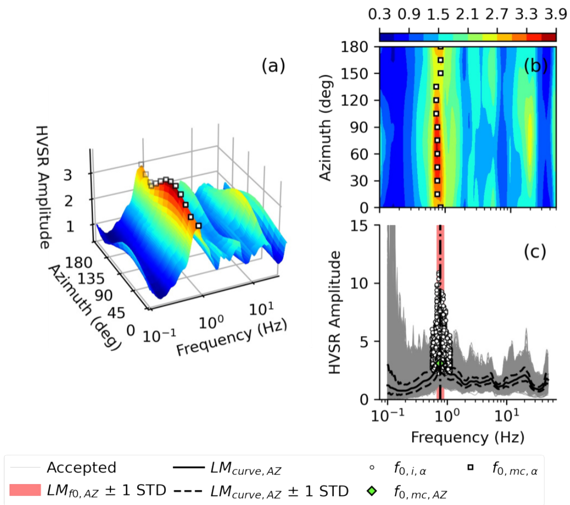


Figure 67: ST4 January 01, 2023; Data Duration: 24 hours

Hence, we can conclude from the obtained results that the effect of the duration of Data on DHVSR is noticeable on the values of peak frequency but minuscule on the azimuth.

Effect of Application of High Pass Filter on DHVSR

As we saw in the traditional hvsrpy generated results, the application of a high-pass filter affects the results, but only at Site A. For Site B, the effects are nearly noticeable.

Site A

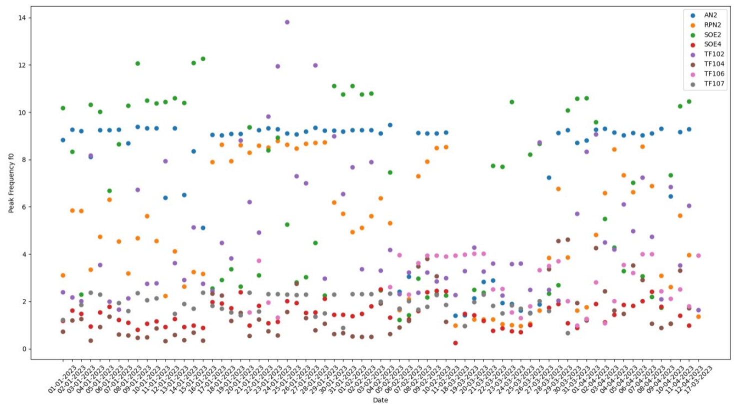


Figure 68: Site A f0 Values over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data.

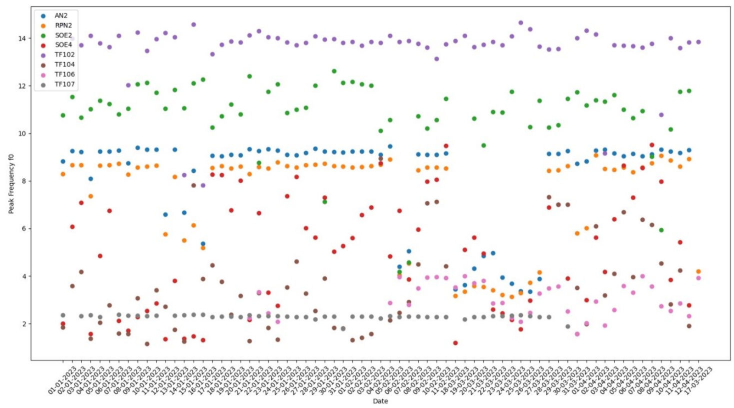


Figure 69: Site A f0 Values over time with minimum frequency of 1 Hz (Applied a high pass filter). Each Value is calculated with 24 hours of data.

The change is quite visible for stations TF102 and TF107; the application of the filter made their data more consistent. However, it decreased the consistency for stations SOE4 and TF104.

Site B

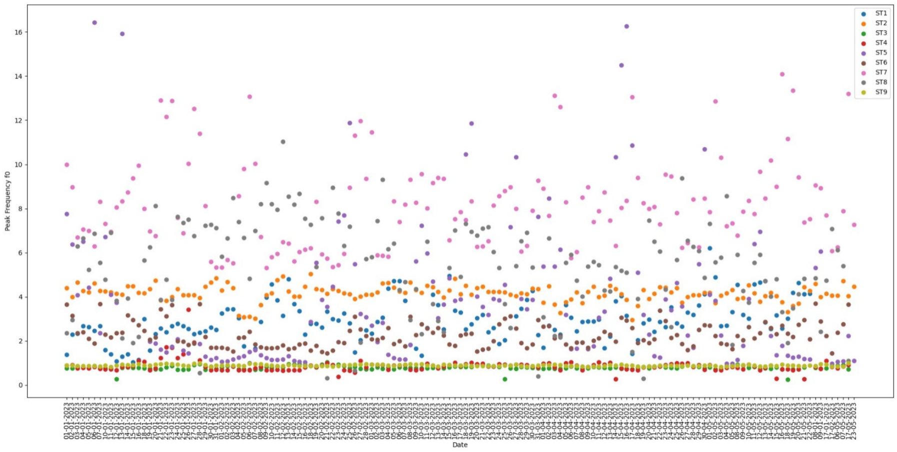


Figure 70: Site B f0 Values over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data.

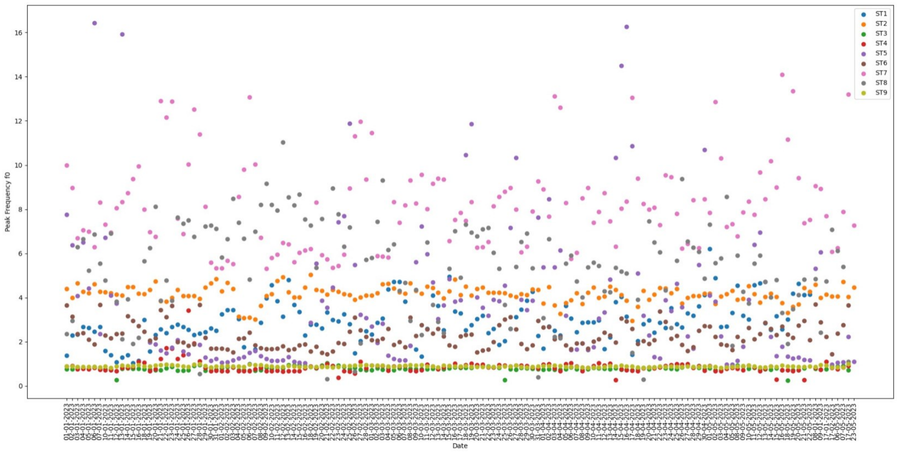


Figure 71: Site B f0 Values over time with minimum frequency of 1 Hz (Applied a high pass filter). Each Value is calculated with 24 hours of data.

For Site B, the change was very small and unnoticeable.

Hence, we can conclude that the results produced by the application of a low-pass filter vary based on site, data collected, and, of course, the corner frequency of the seismometer. For this research, to maintain consistency, we only considered the results obtained by application of 0.1 Hz high pass filter for all sites.

Effect of Change in Ambient Seismic Wave field on Azimuths

To get a better understanding of the subsurface, a Vertical Seismic Profiling (VSP) survey was carried out at Site B on 16th March 2023. We took this opportunity to understand the effect of a 'new noise source' or change in the ambient noise wave field on the results.

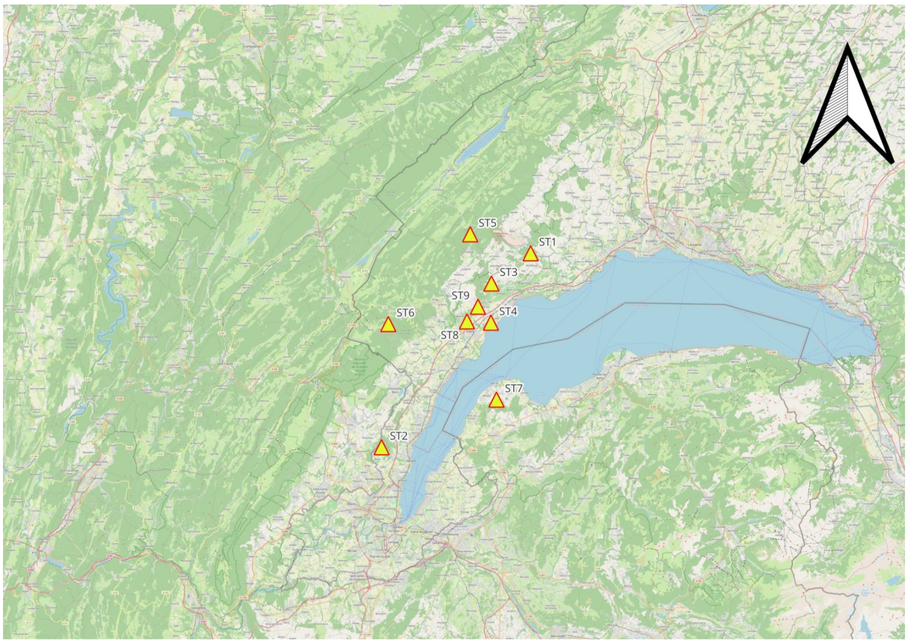


Figure 72: *Station Layout for Site B*

The Vibroseis was placed next to Station "ST9" (see Figure 72 for layout), and sweeps of varying lengths were injected from approximately 6 AM in the morning to 1 Pm in the afternoon. Of course, the injection of sweeps was not continuous, but it can give us an ample understanding of the effects that we want to study.

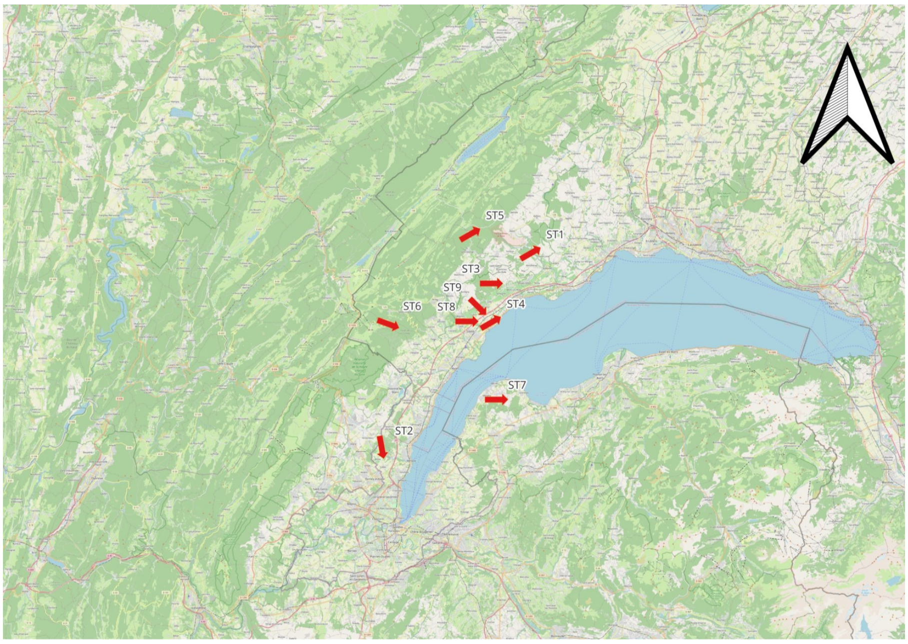


Figure 73: *Average Azimuth for each station at Site B*

First, we obtained the azimuth of each station from the data collected before sweep injection. The results are shown in Figure 73.

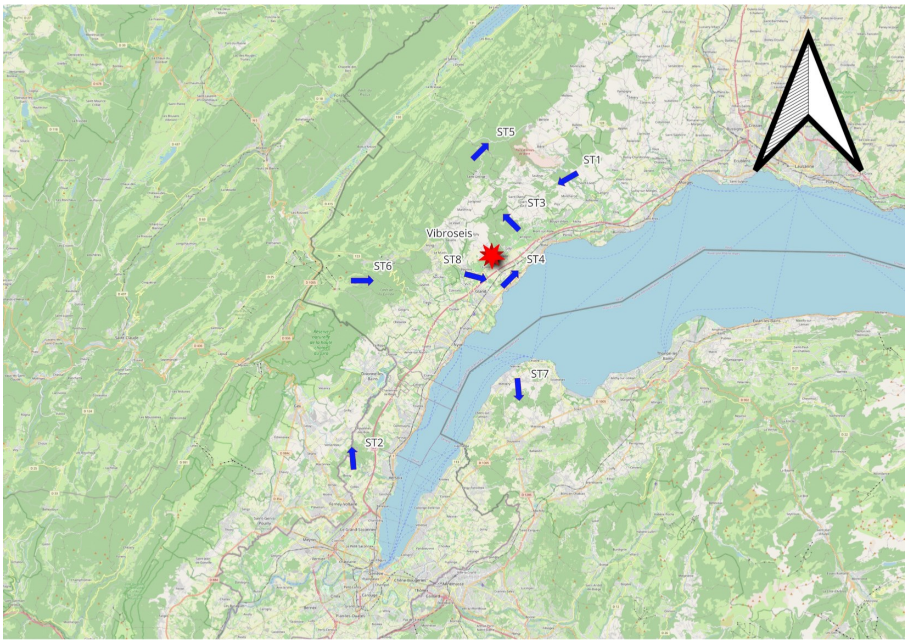


Figure 74: Azimuth during deployment of Vibroseis, for each station at Site B

We then took the data recorded by all the stations, except ST9, and produced DHVSR plots based on the data collected from 6:43 Am to 1:14 Pm (start and end of sweep injection). These plots were used to get the Azimuths of stations as shown in Figure 74.

From the results we can conclude that change in Ambient Noise wave-field do effect the Azimuths obtained by DHVSR.

Furthermore, from the values of the peak frequency obtained before and on the day of VSP, we can conclude that the change in the ambient noise wave field does have an impact on the f0 values; however, it does not produce a significant difference from the average value:

Station Name	Peak Frequency before 16th March	Peak Frequency on 16th March
ST1	2	1.3
ST2	3.5	3
ST3	1	1.5
ST4	0.7	0.8
ST5	1.3	1.5
ST6	2.3	1.3
ST7	7	6
ST8	6	6.3
ST9	0.9	-

Table 1: Peak Frequency obtained before and on the day of weep injection, for every station

Final Results using hvsrpy Azimutal Package

Site A (2022)

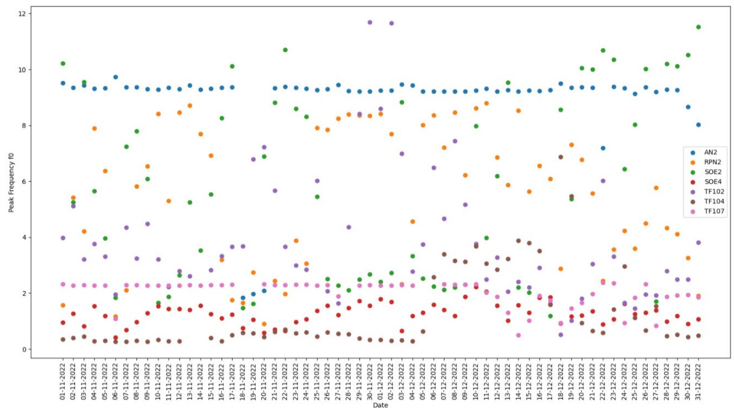


Figure 75: *Site A f0 Values, for all stations, over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data of 2022 (November - December)*

Site A (2023)

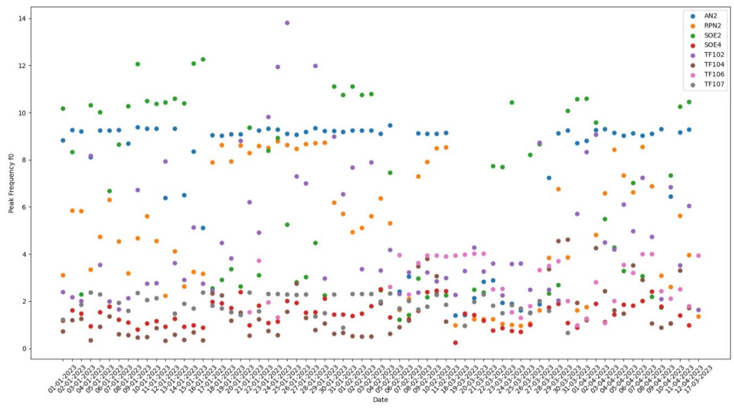


Figure 76: *Site A f0 Values, for all stations, over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data of 2023 (January - April)*

Site B (2022)

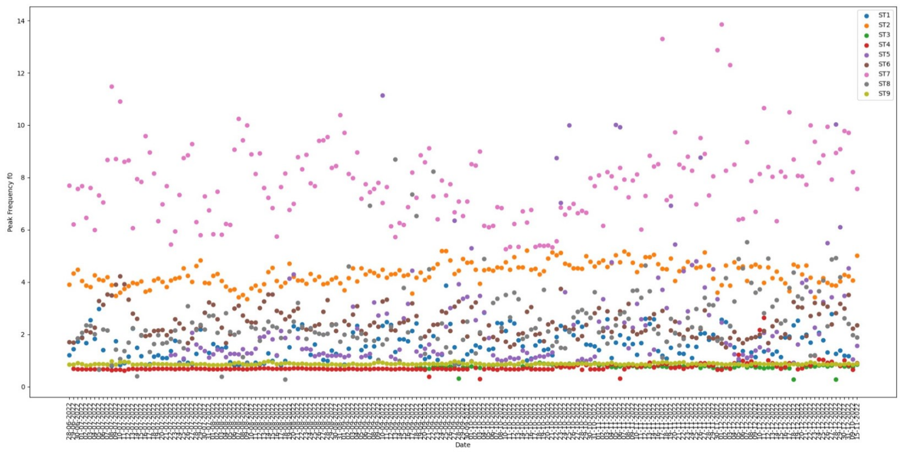


Figure 77: Site B f0 Values, for all stations, over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data of 2022 (June - December)

Site B (2023)

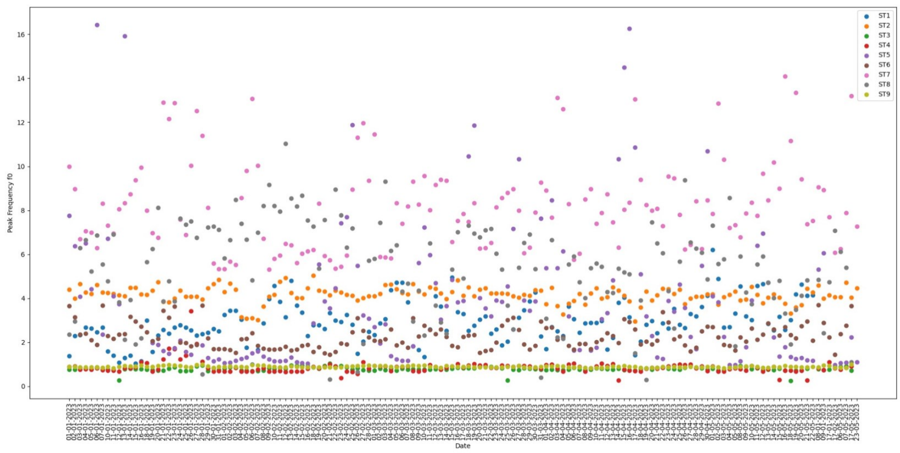


Figure 78: Site B f0 Values, for all stations, over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data of 2022 (June - December)

With all the results obtained, we can conclude that the results produced by the hvsrpy Azimuthal Variability package is consistent and reliable. With this not only can we obtain peak frequency values of out site and use it as a metrics for QC of out seismic station, but also we can get an idea of the pattern of Ambient Seismic Wave-field at the site with the help of Azimuth obtained. In addition, the azimuth responds to changes in the wave field without changing the f0 values, which can be further used to characterize the noise field around the seismic station.

Part Fifteen

Site C: AGSM AIMS (Vicenza, Italy)

Introduction

In April 2023, a seismic monitoring network was installed, the objective of which was to observe and detect any seismicity resulting from the exploitation of the "Vicenza" geothermal resource. In May 2022, the correct functionality of the stations and network was verified, and some fine-tuning activities were conducted (both remotely and through a visit to the sites). The network was fully operational from June 1, 2023, the date of the start of the seismic monitoring.

The installation activity was carried out by a team of three people, two from Isamgeo, including the author of this thesis, and took place between April 11 and 17, 2023, for a total of five working days. Through a preliminary inspection, it was possible to define the location of the four acquisition sites intended to host the monitoring equipment, all of which fell within areas owned by the company Viacqua S.p.A., which made them available to the client company AGSM AIM Calore S.p.a.

This installation was performed after the development of the HVSR method for QC, and the learning from Site A, Site B and SESAME Guidelines were used for the deployment and maintenance of Seismic Stations. Triton Seismometers with a corner frequency of 1 Hz were used for all seismic stations.

In Total Four Seismic Stations were deployed:

1. APOLE
2. BERTE
3. CROCE
4. LOBIA

Figure 79: Seismic Stations deployed at Vicenza, the red and blue circumferences indicate the distance of 3 and 5km from the well

Seismic Station Information

APOLE

The station is located within the area of the Abbadia Polegge power plant, positioned between the artificial hill that covers the two water settling tanks and the northern enclosure of the area. The solar panel was mounted on a pole placed at the edge of the roof of the entrance building to the settling tanks. The concrete pitch was approximately 15 m from the photovoltaic panels.

Figure 80: Seismic Station platform built in accordance with SESAME Guidelines

Figure 81: Triton Seismometer with corner frequency of 1 Hz, placed after removing 1 meter of top soil

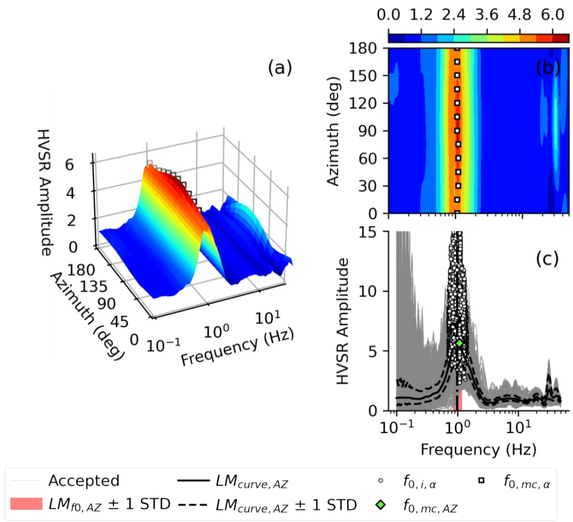


Figure 82: DHVSR for date 1st June 2023

BERTE

This station is located inside the Bertesinella power plant.

Figure 83: Seismic Station BERTE

Figure 84: Seismometer BERTE

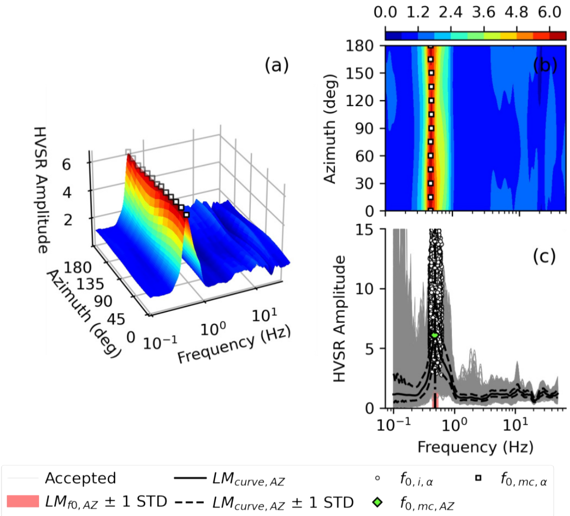


Figure 85: DHVSR for date 1st June 2023

CROCE

The Monte Crocetta station was installed inside a hill that covered the drinking water settling tanks of the Monte Crocetta plant along a service tunnel. A seismometer was placed directly over the concrete flooring inside the service tunnel. A Generator is present in the vicinity of the sensor, which can induce noise in data.

Figure 86: *Seismometer deployed on the rigid concrete floor*

Figure 87: *Service tunnel in which the sensor is deployed*

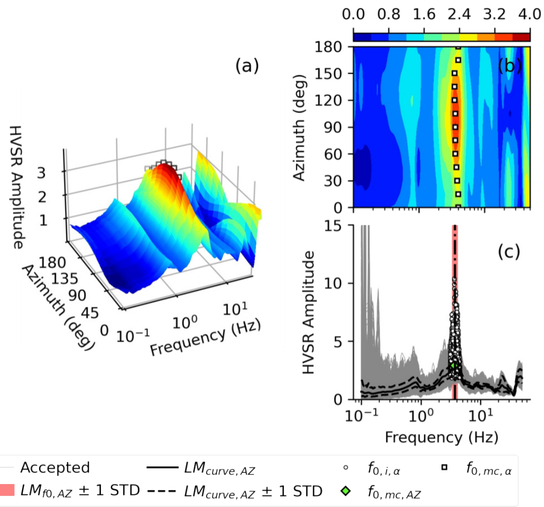


Figure 88: *DHVSR for date 1st June 2023*

LOBIA

Located inside a fenced perimeter. A small water pump is present in the vicinity of the sensor, which can induce periodic noise.

Figure 89: *Seismic Station LOBIA*

Figure 90: *Seismometer LOBIA*

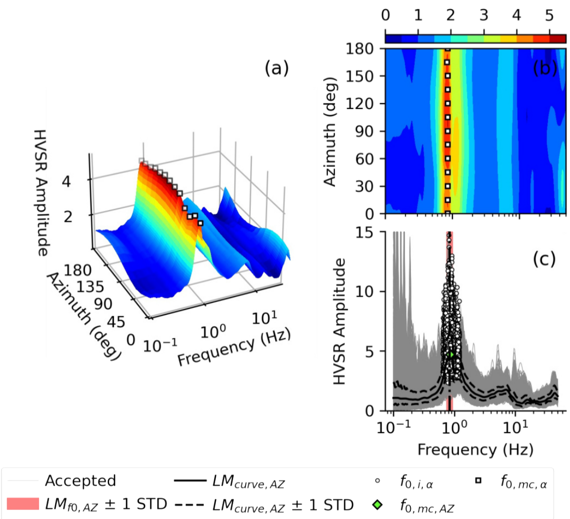


Figure 91: *DHVSR for date 1st June 2023*

Peak Frequency Values Overtime

As shown in Figure 92, the peak frequency values obtained over time are consistent. As mentioned earlier, the straighter the plot of f0 vs. time, the better the health of the station.

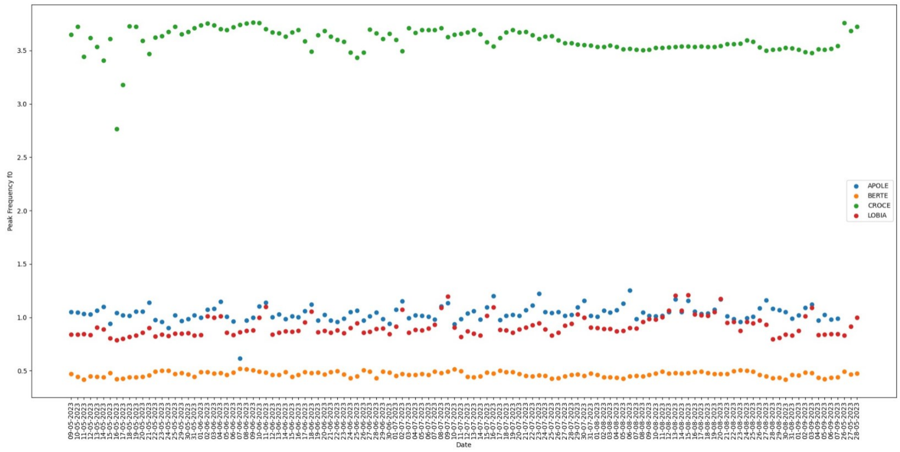


Figure 92: *Site C f0 Values, for all stations, over time with minimum frequency of 0.1 Hz. Each Value is calculated with 24 hours of data of 2023 (May - September)*

Part Sixteen

Conclusion

This study aimed to develop a new method for the Seismic Noise assessment and Network QC of Short-Period Seismometer; further, we wanted to make sure that the developed method was not only accurate and industry ready, but also was compatible with existing deployed equipment.

To accomplish the aforementioned target, we used the Nakamura Technique as the base and developed a new method, which is a set of procedure and Comparative Analysis which would look as follows:

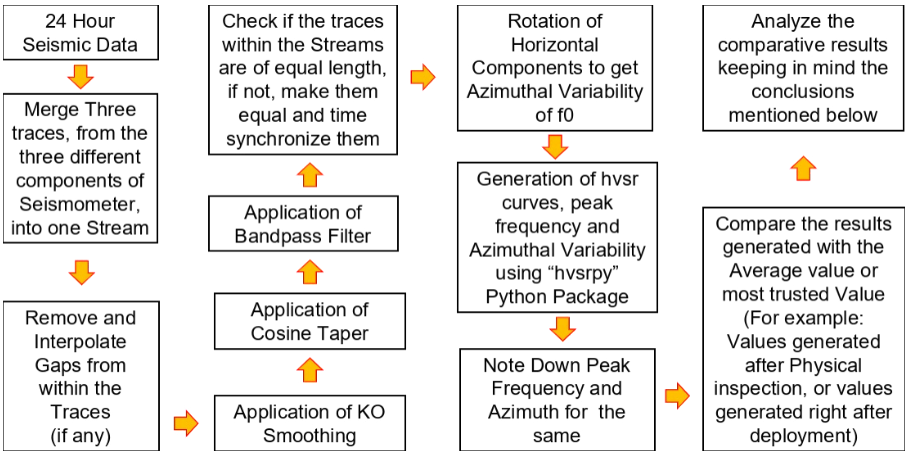


Figure 93: Work flow for the method developed

To support the credibility of the proposed method we collected several empirical proofs from currently on-going projects and got many interesting outcomes.

Here are some of the Key Learnings:

- All software tested in this study showed similar and consistent values of site peak frequency 'f0' with respect to time.
- The Duration of Data had a negligible effect on the results. However, the use of longer durations, especially 24 h, is recommended for Network Quality

Control.

- The application of a high-pass filter or band-pass filter varies from one site to another, as does the equipment used.
- As suggested by SESAME, it is recommended to use KO smoothing
- The HVSR curve corresponds to the PPSD curve, but the former also produces a peak frequency, which can be used as metric for QC of Seismic Stations.
- The change in the ambient noise wave field at the site affects the azimuth obtained by the DHVSR; however, it does not affect the peak frequency values.
- ‘Good Practice’ has to be adopted for physical deployment and maintenance of Seismic Stations. As evident from the results, it plays a significant role in the quality of data produced.

From the above mentioned learning we can conclude that:

1. If the peak frequency of the Seismic Station changes, but the Azimuthal Direction doesn’t change much, it indicates **issues with the ground-sensor coupling**
2. If the peak frequency remains constant but the Azimuth changes, it indicates **a change in the Ambient Noise Wave-field around the station**
3. If both peak frequency and Azimuth changes a lot, it indicates **issue with the instrument or/and total decoupling**
4. **Correct deployment**, in accordance with the SESAME Guidelines and learnings from this thesis, keeps the Seismic Station healthy over time.

The peak frequency values generated by this method over time, can be used to get an Average Peak Frequency value for each station, this Average Peak Frequency can be used as a comparative metric to estimate the health of the Seismic Station, which makes this method a great tool that can be used to replace a more visual tool like PPSD or used with PPSD to get additional information on Seismic noise analysis and QC of Seismic stations.

Part Seventeen

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Part Eighteen

Appendix

Guidelines for Single Seismic Station
——Deployment and Intervention——

PART 1: Deployment Guidelines

i. Before deployment: Have a look at the geological data or log data or Geo-technical data available; especially, types of geological formations, depth of bedrock, 2D-3D structures and level of fracturing on bedrock
ii. If the geological data is available use the formula below to estimate the "fo" or "f_{rn}" value. If the fo value is lesser than the natural frequency of seismometer or if we are interested in getting fo which is lower than the natural frequency of the sensor; another sensor should be used with a higher period. 20s sensor is one of the best range as the period is high enough to record the microseisms and low enough to avoid stability issues.

$$f_{rn} = (2n+1)(V_s / 4Z);$$

f_{rn} = Resonant frequency
n = nth mode
V_s = Shear wave velocity
Z = Sediment Thickness

iii. For microzonation studies, grids with large spaces are suggested: 250m (in case of lateral variation) to 500m spaced grids.
iv. For in-situ coupling:
   - Concrete, Asphalt and pavement: Good Result
   - Soft/irregular soils, grass, ice, gravel, uncompacted snow, etc: Bad Results
   - For low duration results it is best to directly setup sensor on the ground; but in case of special situations like steep slope or if the sensor is deployed for a long duration, artificial soil-sensor coupling is recommended.
   - Grass itself doesn't affects result; however, it affects the soil sensor coupling plus the wind blowing over grass can create high perturbation.

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- Soft soils, water saturated soils, newly ploughed soils, cohesion-less gravel etc can create perturbations, it is better to remove the top superficial soft organic soil and find firm ground or find a firm site a few meters away, before deploying the sensor.
- When recording on Ice or Snow; Firstly, check if the instrument is compatible to work at lower temperatures. Secondly, try to find a place with compacted snow or try to compact the snow artificially. Further it is recommended to install the sensor on a metal or wooden plate to avoid sensor tilting when the snow melts.
- In case is there is a need for Artificial Sensor (such as a metal plate or barrel with sand): Firstly, it is highly recommended to perform a test (for instance a 24 hour recording) before the installation of artificial sensor. Secondly, soft or non-cohesive materials such as foam-rubber, cardboard, gravel, etc as Artificial soil-sensor medium. Thirdly, there is no need to bury the sensor with sand; however, doing so can remove the low wind perturbations.
- Structures, such as Tree, pole, etc near the sensor can induce low frequency perturbations, so a site should be selected keeping this in mind.
- Do not put any load directly on the sensor
- On asphalt or in the sensor in a hole, the effects of wind are negligible, So it is recommended to install the sensor in a hole.
- Avoid measuring above pipes, basements, sewer lids, etc. They significantly affect the vertical motion.

v. Weather Conditions:
   - Avoid taking measurements on windy days.
   - Slight Rain has no effect on measurements; however, strong rains can affect the measurements significantly.
   - Temperature conditions provided by sensor manufacturer has to be followed.
   - Low pressure meteorological events generally raise the low frequency noise.

vi. Other disturbances:
   - High Voltage cable: No influence noted

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- All kinds of short-duration local sources: footsteps, car, train: disturb results
- If possible, the sensor should be at-least 20 meters away from the nearest road. Also, the traffic on the road should be noted.
- Avoid measurements near monochromatic sources, such as: construction machines, industrial machines, pumps, generators, etc.

vii. Directives:

- It is "Extremely" Important to keep a record of everything during the deployment and thus it is important to fill the Deployment field Sheet religiously.
- To keep a visual note of everything, it is recommended to take photo of the site before and after deployment.
- Keeping a note of time is another important thing to be taken care of. "Specify the local time-zone."
- Note and take pictures of Structure near the sensor and submit it with the Field sheet.
- Do not skip any procedure without mentioning in the Field sheet, or specify if the actual site has something which is against the guidelines or if the guideline do not cover in that regard.
- Finally, always remember "Bad data is worst than no data.... As we can interpret something which probably don't even exists"

Good-luck!

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Deployment Field Sheet ID:
(IG-DFS-IT-ddmmyy-TFA-FR-ST001)
(IG = Isamgeo, IT = company country iso code[TR = Turkiye], ddmmyy= date:month:year, TFA = Project, FR = project country, DFS = Intervention Field Sheet , ST001 = Station code)

Date:
(dd-mm-yyyy)

On-site arrival Time:
(hh:mm:ss)

Project:
(TFA, Stogit, ...)

Location:
(or nearby city)

Number of Stations
- Superficie:
- Pozzo:

Deployment In-Charge:

Deployment Tech:

Station Number:
(TF102, AN2, ...)

Station Type:
(Description)

Sensor Make
- Company:
- Model:
- Planned Recording Duration:
  (specify — months/days/hh:mm)
- Manufacturing Date:
- Frequency/Period:
- *Other comments:*

GPS
- Type:
- Number:
- *Other comments:*
- Latitude:
- Longitude:
- Altitude:
- Depth: *(in case of pozzo)*

Weather (☑ relevant)

- Wind:
  - ☐ None
  - ☐ Weak
  - ☐ Medium
  - ☐ Strong

  If measured:
- Rain:
  - ☐ None
  - ☐ Weak
  - ☐ Medium
  - ☐ Strong

  If measured:
- Temperature:
  (in Celsius) ____________________

Site conditions: (☑ relevant)

- Ground:
  - ☐ Grass ———> ☐ Tall ☐ Short
  - ☐ Clay ———-> ☐ Dry ☐ Wet
  - ☐ Loamy ——-> ☐ Dry ☐ Wet
  - ☐ Sand ———-> ☐ Dry ☐ Wet
  - ☐ Gravels
  - ☐ Rock
- Ground Covering:
  - ☐ None
  - ☐ Reinforced (steel plates, piles, ...)
  - ☐ Asphalt
  - ☐ Paved (Tiles, wooden, cement, ...)
  - ☐ Others: ____________________

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Are there coupling issues? (☑ relevant) ☐ No ☐ Yes ☐ No issues, but will use Artificial coupling for better long term protection *If yes:* • Slopping ☐ *If yes; measurement:* Solved by: ___________________ *(Artificial coupling, excavating, ...)* • Covered with vegetation ☐ Solved by: ___________________ • Rock ☐ Solved by: ___________________ • Others ☐ Solved by: ___________________	Artificial Ground-Sensor Coupling: ☐ No ☐ Yes *If yes; type:* _______________ Description: (describe the properties of artificial coupling; for instance, if the sensor is kept in the barrel – - what type of material is used to fill the barrel?; - Is the sensor covered with mud; is there a wind protection; - Is the barrel kept below the surface; Dimensions?, etc)
Near Station Structures observed *(if any)*: • Trees – Buildings – Polls – Underground Structures... *(Description, Height, Distance from station)*	*(Only)* If Artificial Ground-Sensor Coupling used, is there a possibility of 24 hour survey directly on ground without coupling mechanism? ☐ No ☐ Yes ☐ This is the 24 hr survey *If yes:* • *ID number of field sheet assigned for Artificial Ground-Sensor Coupling mechanism (pre or post deployment):* ________________________

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PART 2: Intervention

i. Before intervention: Have a look at the deployment and previous intervention field sheet (ID number will be given in the Pre-intervention MEMO)and photos; further, have a look at the geological data or log data or Geo-technical data available.
ii. Go through the memo notes. Problems must have been written and rationalized; however, in field the issues could be totally different.
iii. Check the weather before starting the intervention, if measuring equipment is available, it is recommended to take all measurements.
iv. Before starting with the actual intervention, take photos (if possible) or make notes of the sensor/station and the surroundings. This is very crucial in order to compare the site with the photos or notes from deployment.
v. It is “Extremely” Important to keep a record of everything during the deployment and thus it is important to fill the Intervention field Sheet religiously.
vi. Keeping a note of time is another important thing to be taken care of. “Specify the local time-zone.”
vii. Do not skip any procedure without mentioning in the Field sheet, or specify if the actual site has something which is against the guidelines or if the guideline do not cover in that regard.

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Intervention Field Sheet ID:
(IG-IFS-IT-ddmmyy-TFA-FR-ST001)
(IG = Isamgeo, IT = company country iso code[TR = Turkiye], ddmmyy= date:month:year, TFA = Project, FR = project country, IFS = Intervention Field Sheet, ST001 = Station Code)

Date:
(dd-mm-yyyy)

On-site arrival Time:
(hh:mm:ss)

Project:
(TFA, Stogit, ...)

Location:
(or nearby city)

Number of Stations
- Superficie:
- Pozzo:

Intervention In-charge:

Intervention Tech:

Deployment Field Sheet ID:
Previous Intervention ID(if Any):

Pre-Intervention Photo taken:
☐ No ☐ Yes

Deployment In-charge:

Deployment Date:
(dd-mm-yyyy)

Station Number:
(TF102, AN2, ...)

Station Type:
(Description)

Reason for Intervention: *(Intervention Memo No., Maintenance Check, Recording Issues,...)*

Weather (☑ relevant)

- Wind:
  - ☐ None
  - ☐ Weak
  - ☐ Medium
  - ☐ Strong

If measured:

- Rain:
  - ☐ None
  - ☐ Weak
  - ☐ Medium
  - ☐ Strong

If measured:

- Temperature:
  (in Celsius) ____________________

Change in Site conditions: (☑ relevant)

☐ No
☐ Yes
If yes; describe:
(Building of a new structure or road or any source of noise, Vegetation cover, addition of pavement,...)

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Are there coupling issues? (☑ relevant)

☐ No
☐ Yes

If yes; describe reason:
(Presence of Water, Uncoupled due to unknown reason,...)

Solved by: *(describe)*

- Monochromatic Noise Sources *(if any)*:

(Factory – Pumps – Generators – Heavy machinery ....)

☐ No
☐ Yes
If yes; type: _______________

- Anthropogenic noise observed:

☐ None
☐ Low
☐ High

- Is there a road present within 30 meters of Station?

☐ No
☐ Yes
If yes; describe traffic:
☐ None
☐ Low
☐ High

Post-Intervention Photo taken:
☐ No ☐ Yes

Other Observations and Comments:

Date and Time After Setup is Finished:
(dd:mm:yyyy and hh:mm:ss + Time-zone)

Signature(s) of the Personal Involved:

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Pre-Intervention MEMO:

(IG-MEMO-IT-ddmmyy-TFA-FR)

(IG = Isamgeo, IT = company country iso code[TR = Turkiye], ddmmyy= date:month:year, TFA = Project, FR = project country, MEMO = Memorandum, ST001 = Station Code)

Date of Memo: *(dd-mm-yyyy)* Project: *(TFA, Stogit, ...)* Number of Stations that need Intervention • Superficie: • Pozzo: -	Date of Intervention: *(dd-mm-yyyy)* Location: *(or nearby city)* Intervention In-charge: Jean-Claude Intervention Tech:
Deployment In-charge: Deployment Field Sheet ID: Previous Intervention ID(if Any): Deployment Date: *(dd-mm-yyyy)*	Previous Intervention? ☐ No ☐ Yes *If yes:* Previous-Intervention In-charge: Previous-Intervention Date: *(dd-mm-yyyy)*
Intervening Station(s): *(TF102, AN2, ...)*	Station Type: *(Description)*
Reason for Intervention: *(Intervention Memo No., Maintenance Check, Recording Issues,...)*	
Geological Information:	
Assigned By:	

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