HVSR Analysis of Ambient Noise Data for Subsurface Characterization at Stations in the North-West Himalayan Region

1. Introduction

1.1. Background

The Himalayan region, known for its complex tectonic setting and high seismicity, presents significant challenges and opportunities for geophysical investigations. The ongoing collision between the Indian Plate and the Eurasian Plate has created a zone of intense crustal deformation and frequent subsurface structures for seismic hazard assessment and earthquake preparedness. Seismic activity, necessitating detailed studies of subsurface structures for seismic hazard assessment and earthquake preparedness (Verma et al.2013). Seismic velocity models derived from the analysis of seismic waves, which travel at different velocities through various subsurface materials, are crucial for understanding the subsurface structure. Traditional active-source seismic methods, such as reflection and refraction surveys, provide high-resolution images of the subsurface but are often impractical in remote and rugged terrains like the Himalayas due to logistical and financial constraints. Ambient noise tomography techniques such as Horizontal to Vertical Spectral Ratio (HVSR) analysis leverage naturally occurring seismic noise called microtremors (Bonnefoy-Claudet et al., 2006).

The HVSR method, pioneered by (Nakamura 1989), is based on the analysis of ambient seismic noise to infer the fundamental resonance frequencies of subsurface structures. This technique involves recording ambient noise and calculating the ratio of horizontal (H) to vertical (V) spectral components. Peaks in the HVSR curve correspond to resonance frequencies associated with significant impedance contrasts, such as the interface between sedimentary layers and bedrock. These resonance frequencies can be used to estimate the depth and properties of subsurface layers.

1.2. Objective

The primary objective of this study is to utilize the HVSR method to analyse ambient noise data from three geophysically significant stations in the Himalayan region. The specific technical goals are as follows:

1. Determine the Fundamental Frequency of sites
2. Estimate the approximate depth to bedrock
3. Determine the average Shear Velocity Structure

Identifying the fundamental frequency helps in seismic hazard assessment by highlighting areas prone to seismic amplification, which informs the design of earthquake-resistant structures and aids urban planners in making informed decisions for safe construction practice (Bard, 1999). Estimating the depth to bedrock provides essential data for geotechnical engineering, ensuring the stability and proper anchoring of foundations for buildings, bridges, and other infrastructure. It also supports resource exploration by guiding drilling operations for groundwater and mineral extraction (Fäh et al., 2001). Determining the shear velocity structure is crucial for seismic wave propagation modelling, enabling accurate predictions of ground motion characteristics during earthquakes and facilitating detailed site response analysis (Lachet & Bard, 1994). This information is vital for designing effective seismic retrofitting measures and assessing potential landslide risks, contributing to the overall seismic risk mitigation and resilience of the region.

2. Material and Methodology

2.1 Study Area

The Himalayan range, which began forming approximately 55 million years ago due to the ongoing subduction of the Indian Plate beneath the Eurasian Plate (Powell and Conaghan 1973; Molnar and Tapponnier 1975; Yin and Harrison 2000), is characterized by various thrusts and detachments resulting from crustal shortening. Key structural features include the South Tibetan Detachment (STD), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT), and the Main Frontal Thrust (MFT)/Himalayan Frontal Thrust (HFT). The entire Himalayan belt, based on seismic activity, has been classified into three distinct segments namely; the Western, the Central and the Eastern segment (Molnar & Tapponnier, 1975). For the present work, three stations in the north-western segment of the Himalayas located at 33.3-36.0-degree North latitude and 75.6-79.0-degree East longitude is considered for HVSR analysis. Station details are provided below

1. ADS station

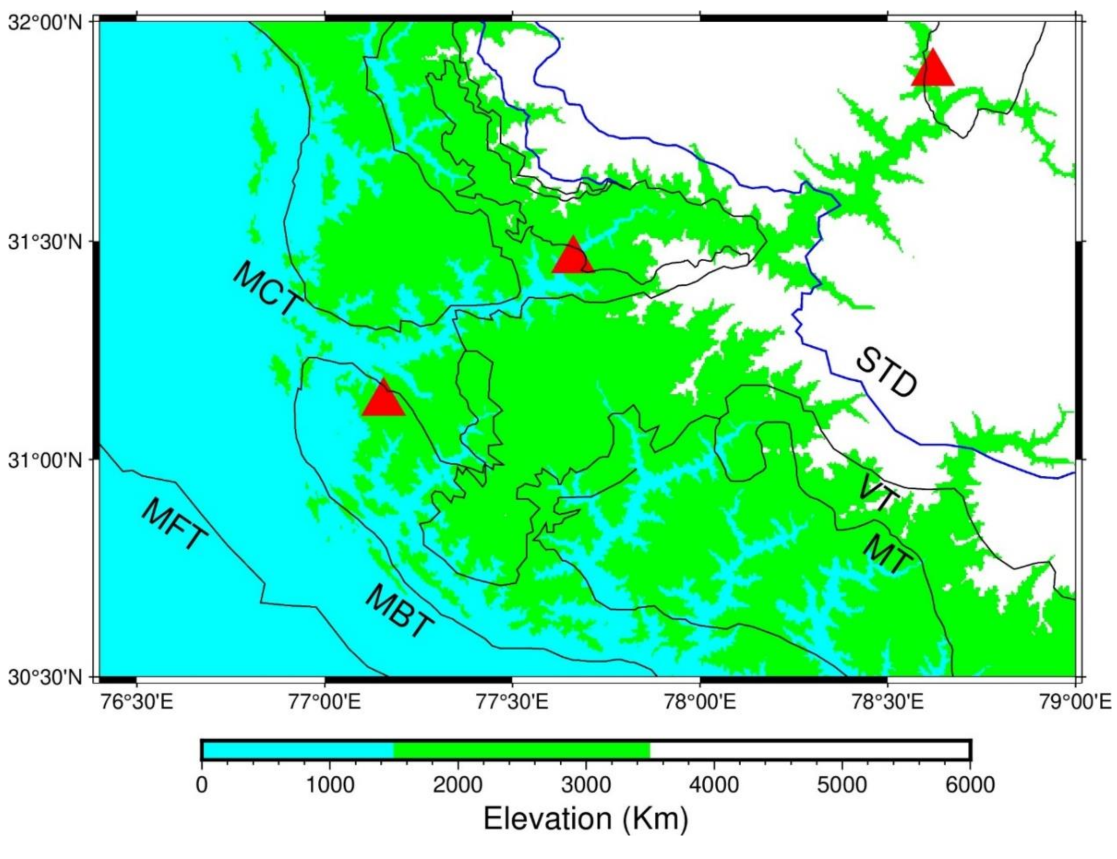
   Latitude 31.1295° N, Longitude 77.1576° E, Elevation 1802m.

2. SRP station

   Latitude 31.4557° N, Longitude 77.6628° E, Elevation 1268m

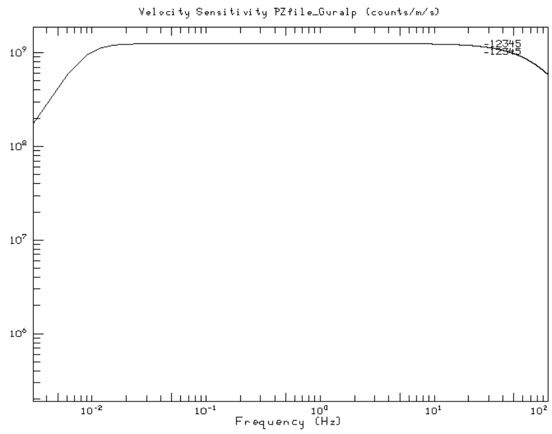
3. NAK station

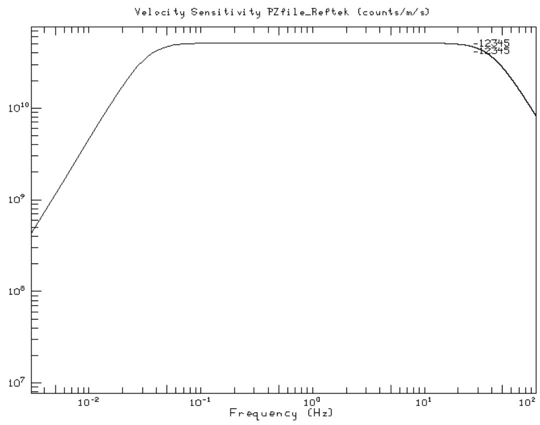
   Latitude 31.8834° N, Longitude 78.6199° E, Elevation 3378m



2.2 Data

At SRP station, a Güralp broadband seismometer, with a recording frequency capability of up to 50 Hz, was utilized. This sensor is renowned for its high sensitivity and broad flat bandwidth range of 0.02 to 23 Hz, making it exceptionally suited for capturing low-frequency ambient noise crucial for HVSR analysis. Conversely, at ADS and NAK stations, Reftek seismometers were employed, each also capable of recording frequencies up to 50 Hz. The Reftek sensors have a flat bandwidth range of 0.07 to 22 Hz, ensuring robust performance within this specified range. One full day of continuous ambient noise data was meticulously recorded at each station to facilitate comprehensive HVSR analysis.





2.3 HVSR Method

The Horizontal to Vertical Spectral Ratio (HVSR) method, introduced by Nakamura (1989), is a widely adopted technique in seismology for characterizing subsoil properties using ambient seismic noise, or microtremors. This method relies on the principle that the horizontal component of ground motion retains soil amplification characteristics, while both horizontal and vertical components reflect source and propagation path effects. By calculating the ratio of the horizontal to vertical Fourier spectra, the HVSR method isolates site-specific amplification from other influences. Peaks in the HVSR curve indicate fundamental resonance frequencies of subsurface layers, which are influenced by shear wave velocity and layer thickness (Lachet and Bard, 1994). The method has been validated for its stability and reliability in various studies, including those by (Yamazaki and Ansary 1997) and (Theodulidis and Bard 1995), who demonstrated its effectiveness in different geological settings. However, the theoretical basis of HVSR method is still debated and different explanations have been given (Nakamura,2000, Bard, 1999, Bonnefoy-Claudet et al., 2006). The HVSR technique is non-invasive, cost-effective, and provides essential insights into local site effects, seismic microzonation, and subsurface geological structures, making it a crucial tool in geotechnical and seismic hazard assessments.

The HVSR method involves recording ambient noise using three-component seismometers. The key steps include data collection, where ambient seismic noise is recorded continuously over a specified period, typically 24 hours for robust analysis. The recorded time-domain seismic signals are then transformed into the frequency domain using the Fast Fourier Transform (FFT) to yield the amplitude spectra of the horizontal (H) and vertical (V) components. The amplitude spectra of the two horizontal components (north-south and east-west) are averaged to obtain a representative horizontal amplitude spectrum, and the HVSR is computed by dividing this horizontal spectrum by the vertical spectrum for each frequency bin. Peaks in the HVSR curve correspond to the fundamental resonance frequencies of the subsurface layers, influenced by shear wave velocity and layer thickness. The fundamental frequency (f_0) identified from the HVSR curve is related to the shear wave velocity (Vs) and the thickness (H) of the overlying sedimentary layers by the equation $\mathbf{fO} = \frac{\mathbf{Vs}}{\mathbf{4H}}$ allowing for the estimation of subsurface shear wave velocities and the depth to bedrock. This method provides valuable insights into the subsurface geological structures and their properties.

The HVSR method is extensively used for seismic micro zonation, mapping local site effects to identify areas susceptible to seismic amplification (Bard, 1999), geotechnical engineering, assessing site conditions for foundation design and other construction purposes (SESAME Project, 2004), and environmental and engineering geology, understanding subsurface geological structures and their dynamic properties (Fäh et al., 2001). The advantages of the HVSR method include its non-invasive and cost-effective nature, requiring only ambient noise recordings, and its ability to provide reliable estimates of the fundamental frequency and insights into subsurface structures. However, it may produce ambiguous results in areas with complex subsurface geology and requires careful interpretation and validation with other geophysical methods for comprehensive subsurface characterization. The HVSR method, with its theoretical foundations and practical applications, serves as a vital tool in seismic hazard assessment and geotechnical investigations, contributing to the understanding of subsurface conditions and their implications on infrastructure and environmental stability.

3. Data Processing and analysis

3.1 HVSR Calculation

The HVSR analysis was performed using the Geopsy software suite, which is specifically designed for Ambient noise data processing and analysis. The steps involved in the HVSR calculation are as follows:

- **Filtering**: A band-pass filter (0.1-20 Hz) was applied to the raw data to remove noise outside the frequency range of interest. This step is crucial for isolating the ambient noise signals relevant to HVSR analysis (SESAME Project, 2004)
- **Windowing**: A total of One-hour data is selected from each station. The continuous seismic data was segmented into non-overlapping 50-second windows. Only the stationary was manually picked for further processing and segments with anomalous amplitude were rejected.
- **Tapering**: A cosine taper was applied to all windows of three components in time domain to minimize edge effects.
- **FFT**: Then Fourier spectra are computed for each individual tapered time window.
- Geometric mean of two horizontal components is taken to make one resultant horizontal spectrum (H= (H_{EW} X H_{NS})^0.5) and divided by vertical spectrum to get HVSR value at each frequency and HVSR curve is obtained.
- **Smoothing:** Curve is smoothed using a Konno-ohmachi window with a smoothing band of 20 % for ease in analysis (Konno et al.1995).
- Frequency range of 0.1 Hz to 15 Hz is chosen for analysis as that is our region of interest.

- Directional energy was analysed at 10-degree intervals to assess azimuthal variations using the formula $H = H_{EW} * \cos \alpha + H_{NS} * \sin \alpha$; where α is angle from North-south direction, H_{NS} and H_{EW} are north-south component and east-west component in time domain respectively.

This procedure is done for all three stations to obtain HVSR curve and dominant frequency and amplification factor of all three stations are found out.

3.2 Inversion of HVSR curve

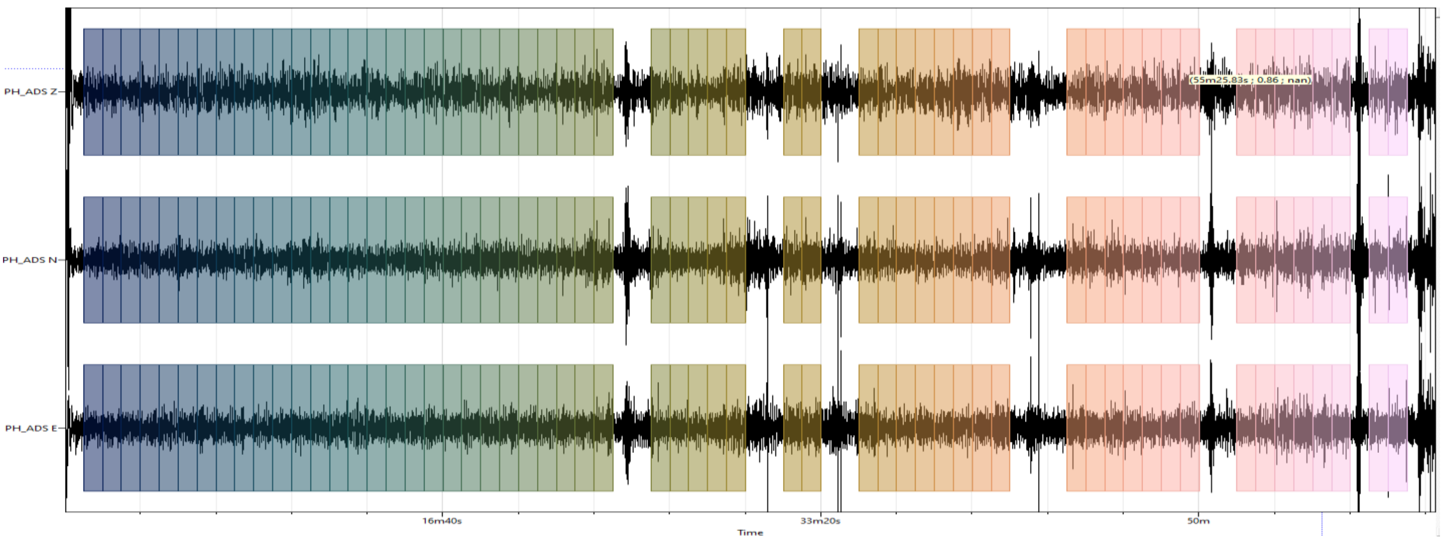
For Inversion of HVSR curve to get Shear wave velocity profile of the sites, HVSRInv software was used. The HVSRInv is a MATLAB-based graphical user interface developed to compute the synthetic HVSR and to estimate the model parameters for each layers such as shear wave velocity, thickness, density and damping ratio from HVSR. This software uses the equivalent linear approach detailed above to compute the synthetic site response. Moreover, the developed inversion algorithm has the feature of elitism, unlike traditional genetic algorithms to perform iterative inversion (Kafadar et al. 2022).

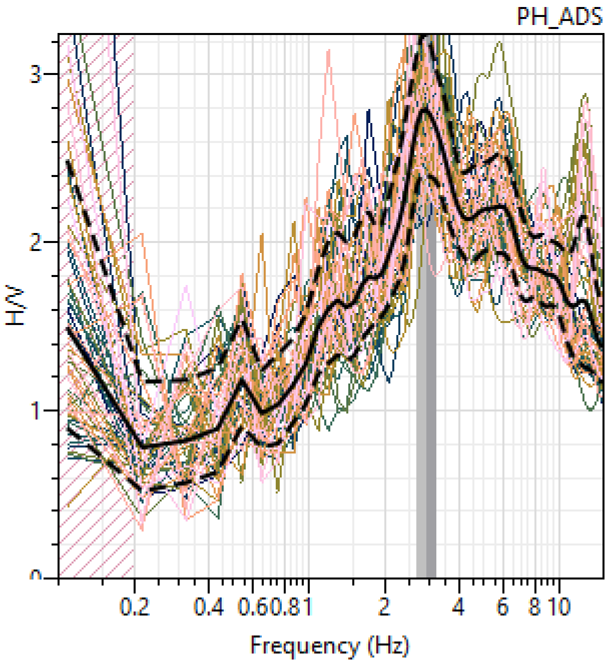
A three-layer subsurface model was chosen as initial model for inversion. Best fitting model after sufficiently enough iterations (i.e. 3000) was chosen as subsurface model.

4. Results

The results of the HVSR analysis for the three stations, SRP, ADS, and NAK, reveal distinct subsurface characteristics that provide insights into the geological conditions of each site.

For the ADS station, the selected time windows, as shown in Figure 1b, provided a stable representation of ambient noise conditions. The HVSR curve (Figure 2b) exhibits a clear peak at 2.94 Hz with an amplification factor of 2.7 along some other indistinct peaks indicating small gradient of velocity in the subsurface. The inversion results (Figure 4b) indicate a shear wave velocity profile with values around 300 m/s near the surface, increasing to 1000 m/s at greater depths, which points to a sedimentary environment with an estimated depth to bedrock of approximately 57 meters. Additionally, the azimuthal variation analysis (Figure 3b), conducted at 10-degree intervals, reveals no noticeable fluctuations in the horizontal-to-vertical spectral ratio, suggesting isotropy in the subsurface structure at this site.




PH_ADS
H/V
Frequency (Hz)
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2
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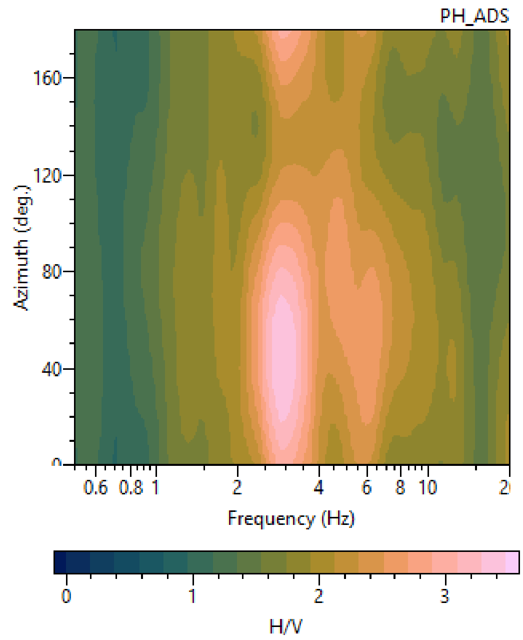
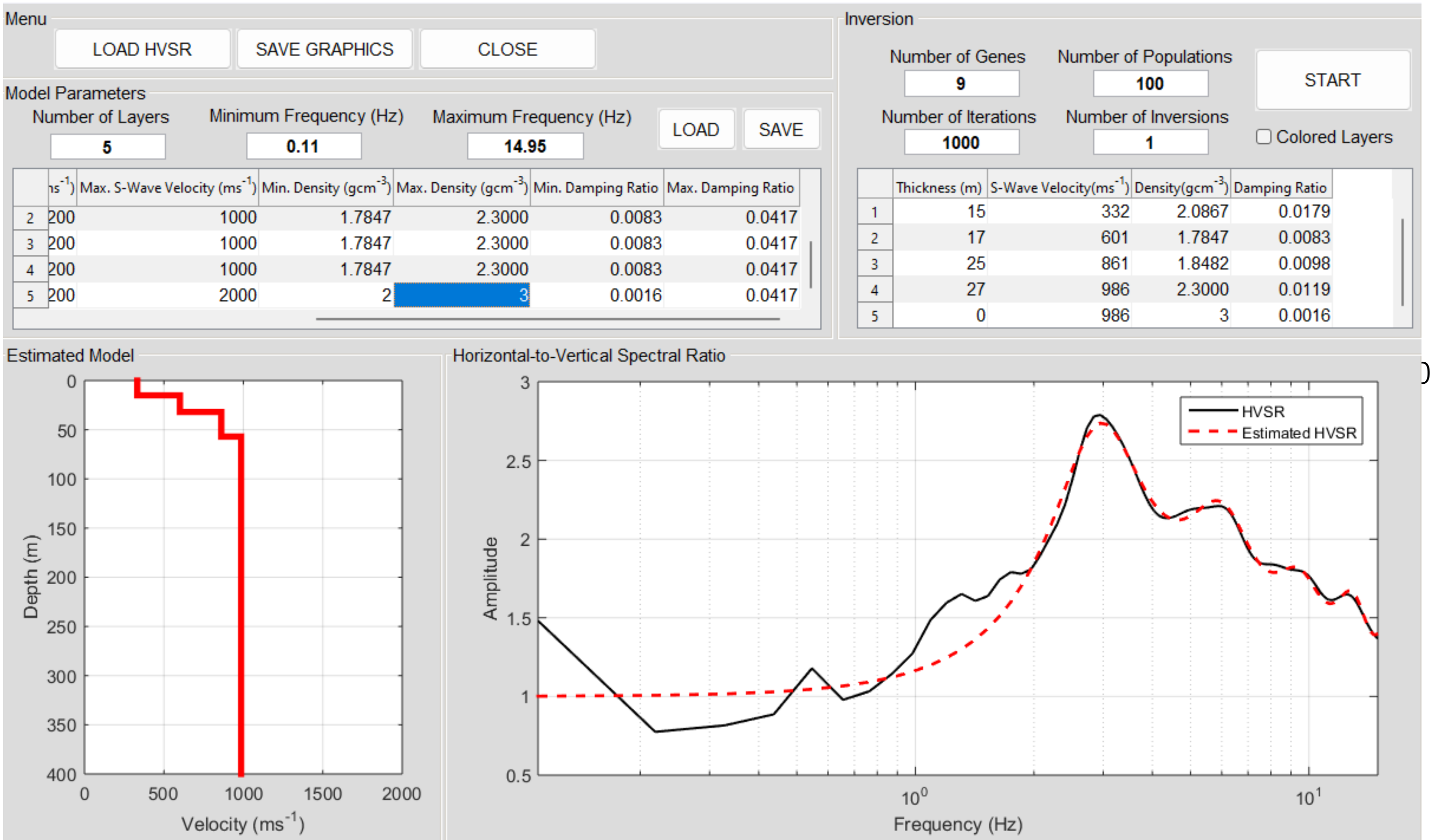

PH_ADS
Azimuth (deg.)
Frequency (Hz)
0.6 0.8 1 2 4 6 8 10
0 40 80 120 160
H/V
0 1 2 3


Menu
LOAD HVSR
SAVE GRAPHICS
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Model Parameters
Number of Layers
5
Minimum Frequency (Hz)
0.11
Maximum Frequency (Hz)
14.95
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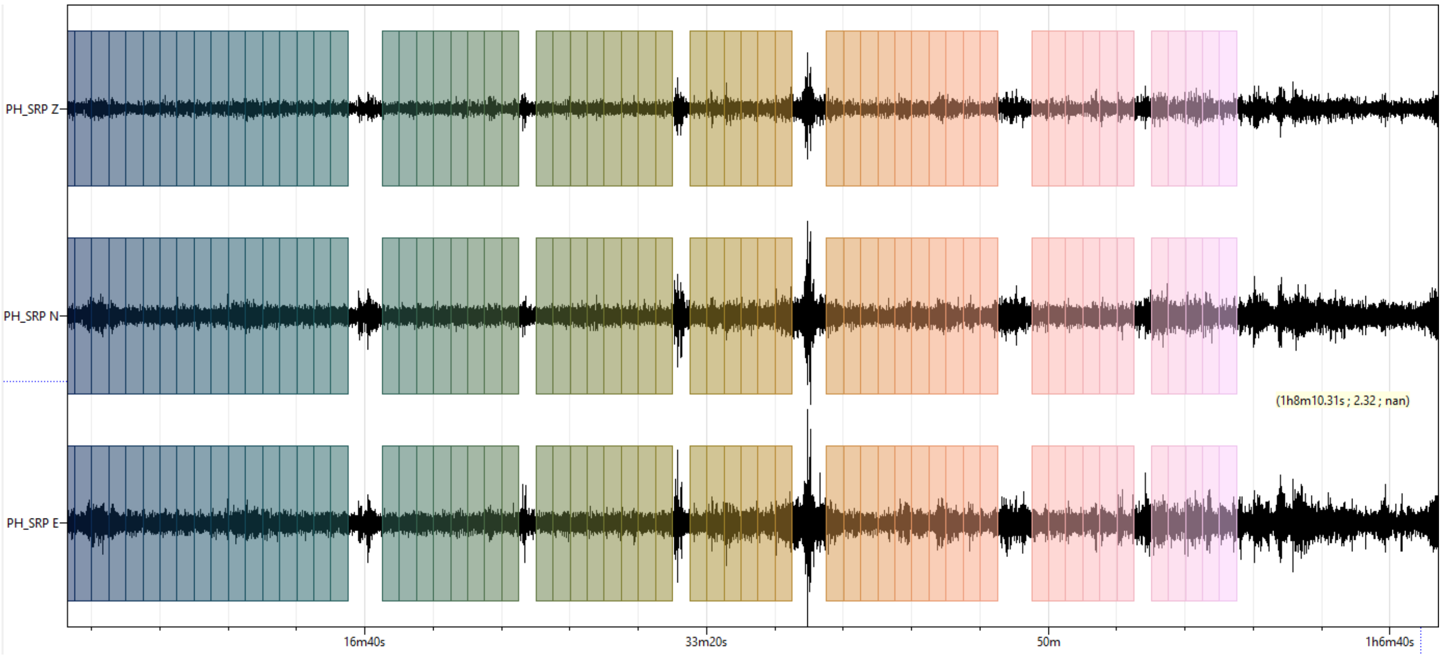
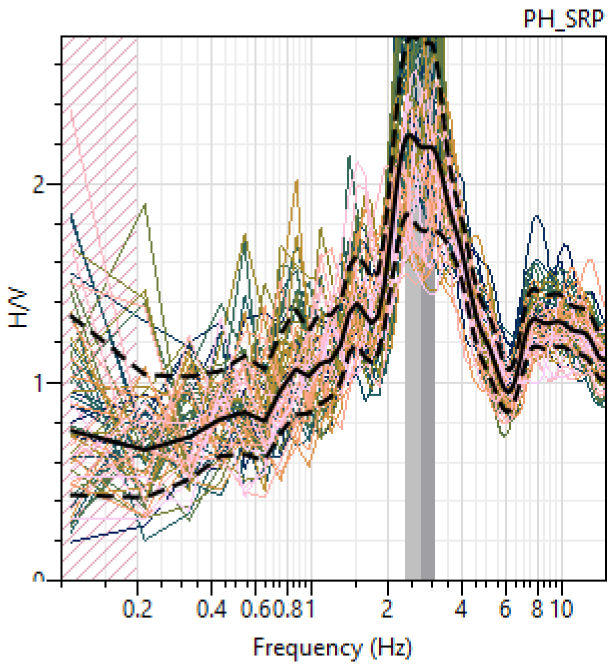
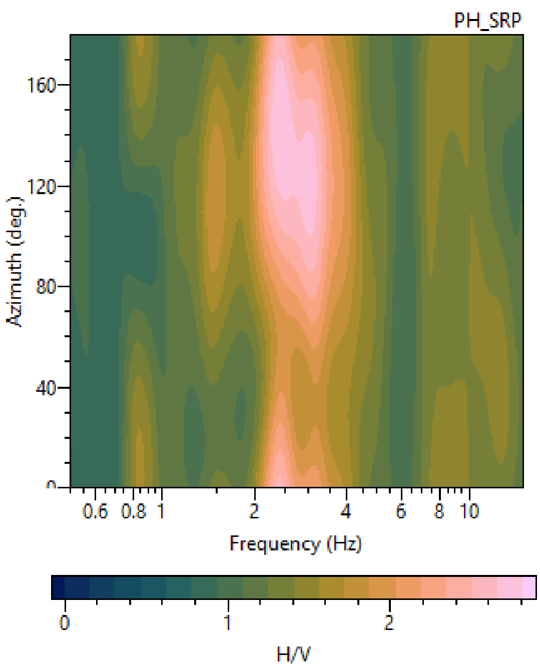
SAVE
Max. S-Wave Velocity (ms-1) | Min. Density (gcm-3) | Max. Density (gcm-3) | Min. Damping Ratio | Max. Damping Ratio
2 200 1000 1.7847 2.3000 0.0083 0.0417
3 200 1000 1.7847 2.3000 0.0083 0.0417
4 200 1000 1.7847 2.3000 0.0083 0.0417
5 200 2000 2 3 0.0016 0.0417
Inversion
Number of Genes
9
Number of Populations
100
START
Number of Iterations
1000
Number of Inversions
1
Colored Layers
Thickness (m) | S-Wave Velocity(ms-1) | Density(gcm-3) | Damping Ratio
1 15 332 2.0867 0.0179
2 17 601 1.7847 0.0083
3 25 861 1.8482 0.0098
4 27 986 2.3000 0.0119
5 0 986 3 0.0016
Estimated Model
Depth (m)
Velocity (ms-1)
0 500 1000 1500 2000
0 50 100 150 200 250 300 350 400
Horizontal-to-Vertical Spectral Ratio
Amplitude
Frequency (Hz)
HVSR
Estimated HVSR
0.5 1 1.5 2 2.5 3

For the SRP station, the selected time windows, shown in Figure 1a, were used to capture stable ambient noise conditions. The HVSR curve (Figure 2a) features a prominent peak at approximately 2.5 Hz with an amplification factor of 2.17 and another at around 8 Hz indicating two sharp velocity gradients, the first associated with sediment-bedrock interface and later due to a shallow discontinuity. The shear wave velocity profile derived from the inversion (Figure 4a) displays velocities of around 460 m/s in the upper layers, increasing to about 1000 m/s with depth, which suggests a firm underlying bedrock with an estimated depth of around 47 meters and a shallow velocity contrast at around 33 meters. The azimuthal variation analysis (Figure 3a), performed at 10-degree intervals, shows a relatively uniform response, implying isotropic subsurface properties at SRP.

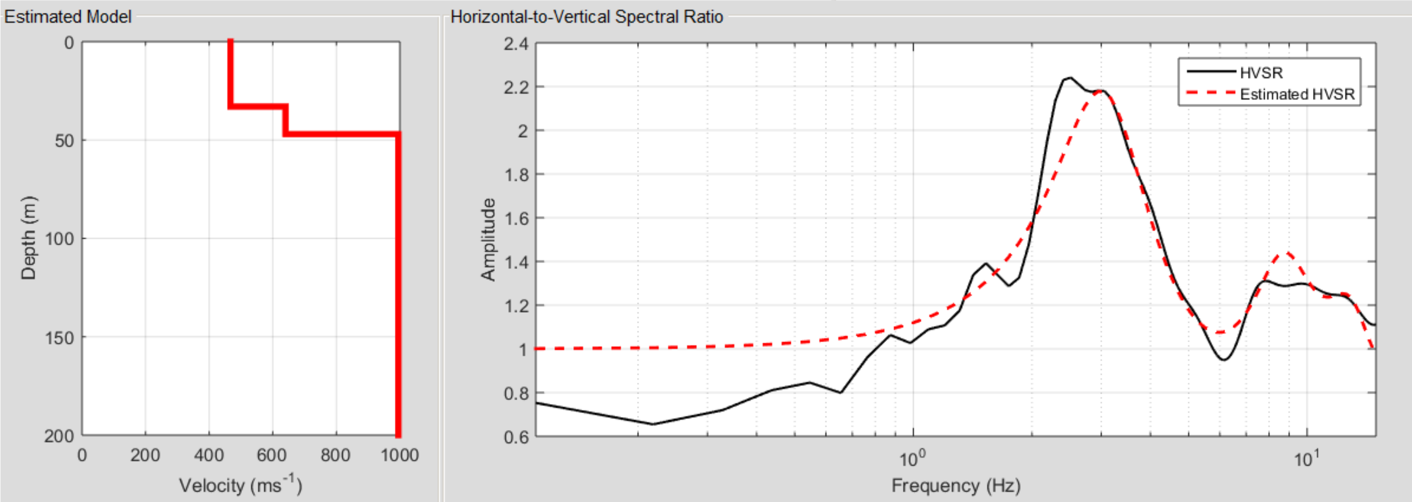




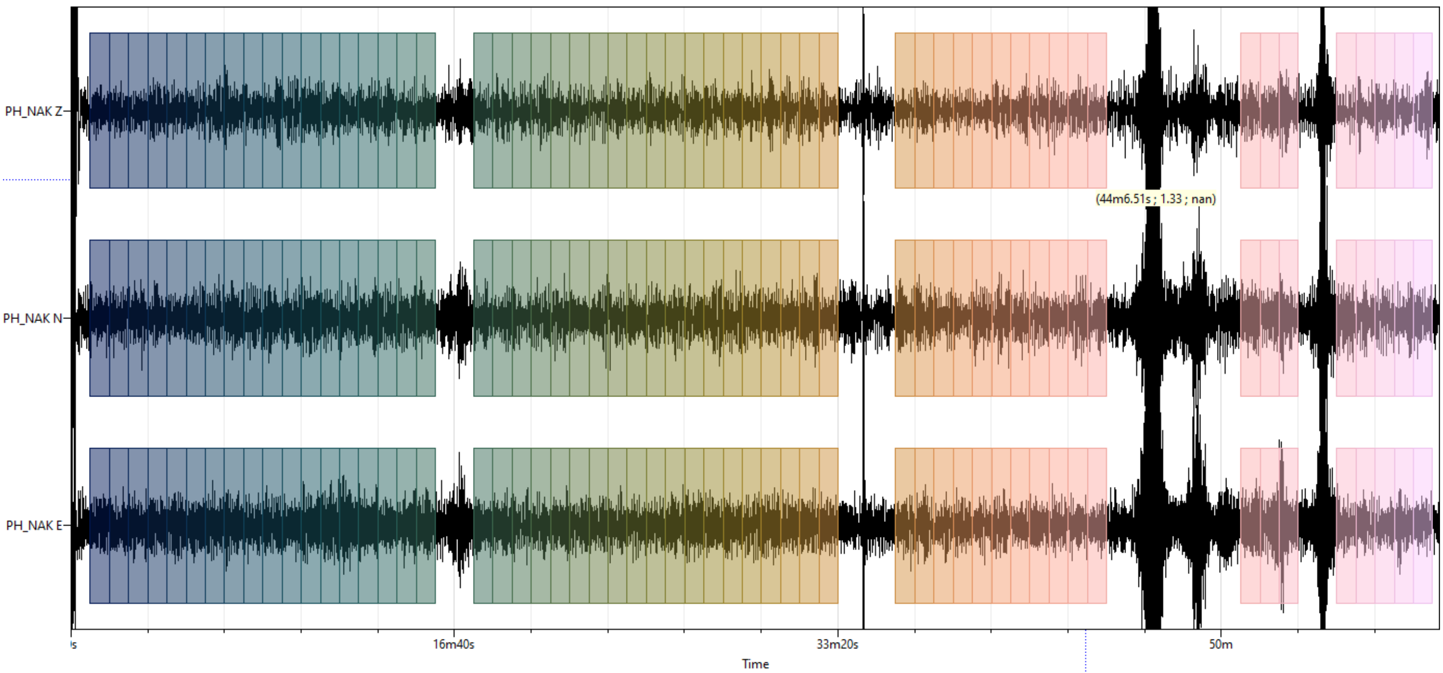


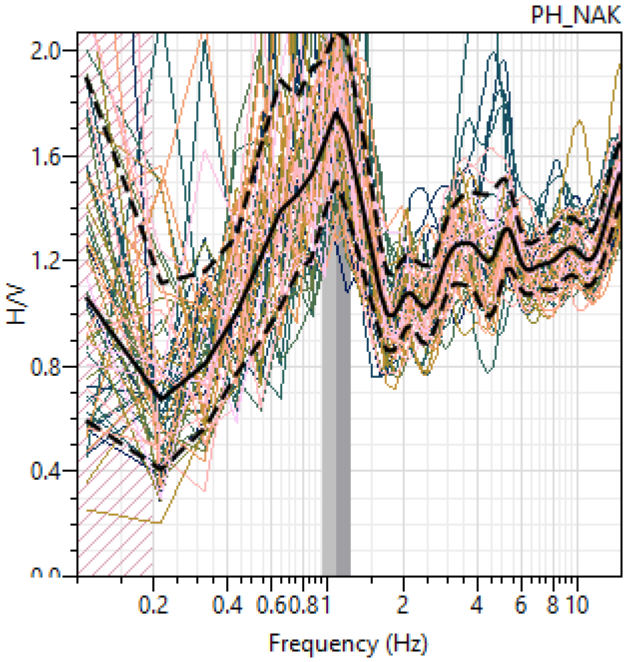
	(ms^{-1})	Max. S-Wave Velocity (ms^{-1})	Min. Density (gcm^{-3})	Max. Density (gcm^{-3})	Min. Damping Ratio	Max. Damping Ratio
1	200	800	1.7847	2.1670	0.0104	0.0417
2	200	800	1.7847	2.1670	0.0104	0.0417
3	400	1000	1.9666	2.2357	0.0083	0.0208

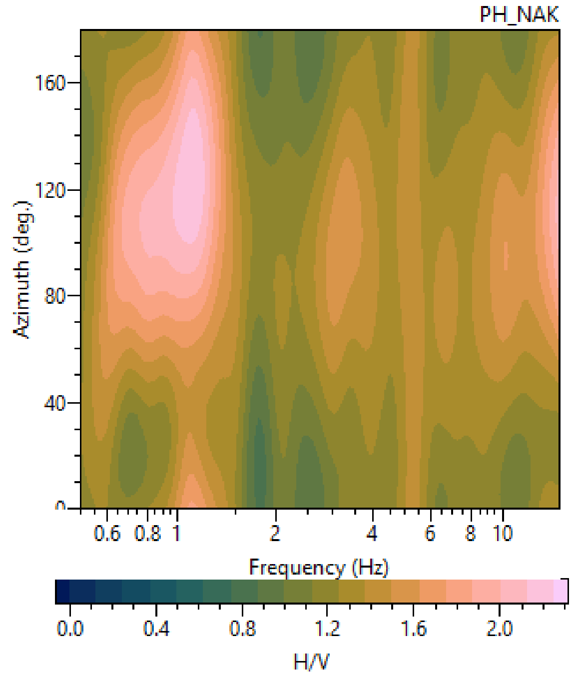
	Thickness (m)	S-Wave Velocity(ms^{-1})	Density(gcm^{-3})	Damping Ratio
1	33	467	1.7892	0.0417
2	14	640	2.0720	0.0417
3	0	995	2.2357	0.0083

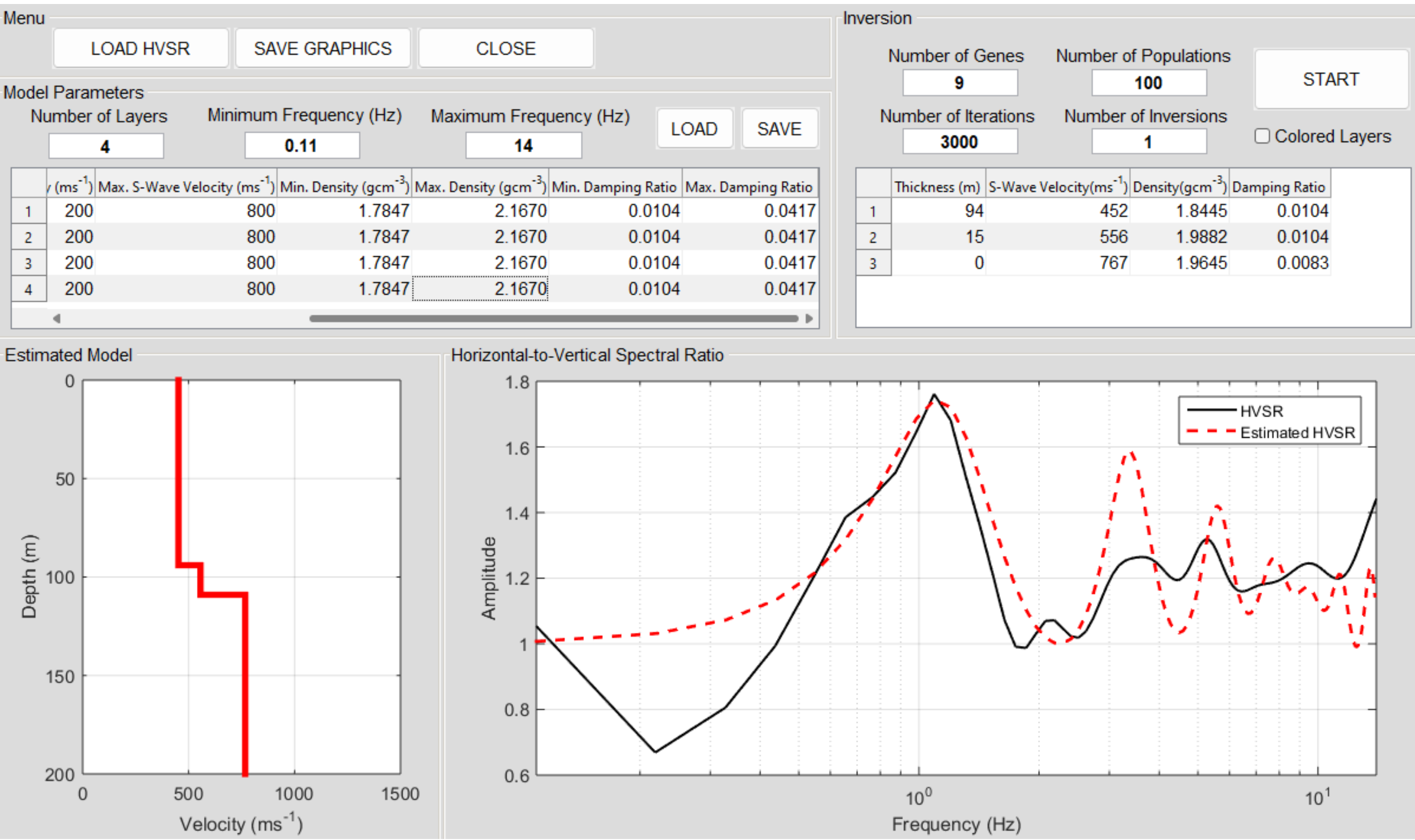


For the NAK station, the selected time windows, as depicted in Figure 1c, were analysed to ensure stable ambient noise recordings. The HVSR curve (Figure 2c) shows a distinct peak at approximately 1.092 Hz suggesting a deeper bedrock with an amplification factor 1.75. The shear wave velocity profile obtained from the inversion results (Figure 4c) reveals velocities starting at about 450 m/s near the surface and increasing to around 760 m/s with depth, suggesting moderately consolidated subsurface layers with an estimated bedrock depth of approximately 110 meters. The azimuthal variation analysis (Figure 3c), conducted at 10-degree intervals, indicates a relatively consistent response across different orientations, suggesting minimal anisotropy in the subsurface structure at NAK.









Station	Fundamental frequency	Amplication factor	Bedrock depth
ADS	2.94	2.7	57
SRP	2.5	2.17	47
NAK	1.092	1.75	110

5. Discussion

The HVSR analysis across the three stations reveals significant insights into the geological evolution and seismic hazard potential of the North-West Himalayan region. The variation in bedrock depth and shear wave velocities across the sites suggests that the region is characterized by complex subsurface heterogeneity, likely influenced by the tectonic processes associated with the ongoing collision between the Indian and Eurasian plates. The deeper bedrock observed at NAK, along with its lower fundamental frequency, may indicate a history of more substantial sediment deposition or slower tectonic uplift in this area compared to ADS and SRP. This could reflect a localized zone of crustal extension that has trapped sediments over geological time.

From a hazard assessment perspective, the differences in fundamental frequency and amplification factors among the stations highlight the variable seismic risk across the region. Sites like ADS, with a higher fundamental frequency and lower bedrock depth, may experience more significant amplification of higher frequency seismic waves, potentially leading to greater damage to shorter, more rigid structures during an earthquake. Conversely, the lower frequency resonance at NAK suggests that this area might be more susceptible to the amplification of longer-period seismic waves, which could pose a higher risk to taller or more flexible structures. These site-specific variations in seismic response emphasize the need for tailored seismic hazard assessments and mitigation strategies that consider the unique geological and geotechnical characteristics of each location. The isotropic nature of the subsurface as indicated by the azimuthal variation analysis supports the reliability of these assessments, as it suggests consistent seismic wave propagation characteristics in all directions.

Further studies can build on these findings by integrating other methods, such as Multichannel Analysis of Surface Waves (MASW) or Dispersion Curve Analysis, to validate and complement the HVSR results. Joint inversion techniques, as suggested by Ikeda et al. (2013) and Giancarlo (2010), could be employed to achieve better resolution and depth of the velocity profile. The interpretation of results can be further enhanced by incorporating data from boreholes, geological maps, and geotechnical characteristics, offering a more detailed subsurface model. Comparing and complementing these findings with other geophysical methods will provide a more comprehensive understanding of the region's seismic risk. Additionally, incorporating information on past earthquakes and the area's known tectonics is crucial for effective seismic micro zonation, ensuring the safety and resilience of infrastructure across the North-West Himalayan region.

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