Developing a high-resolution near-surface velocity model using the microseismic data

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Abstract

Near-surface models are essential in identifying the optimum depth for placing the seismic explosive to acquire the seismic data and understand the weathered layer changes. Conventionally, Near-surface models were developed using the upholes acquired at defined regular intervals in the operational area. Instead of using Uphole data, microseismic data can be used to generate high-resolution near-surface models. In this study, we have analyzed three-component passive ambient noise for developing high-resolution velocity models, which could be used to understand the weathered layer (Low-velocity layer) changes and optimum depth identification at each uphole location. The Horizontal-to-vertical spectral ratio (HVSR) of the shear wave (Vs) technique uses three-component seismic noise to determine the geological interfaces at different depths. This technique can estimate the velocity variations at different interfaces with various frequency ranges of seismic noise. It creates a 1D geological/Velocity model with physical properties contrast for each depth at the acquired locations. The results at all locations were interpolated, and continuous two-dimensional velocity models were developed. The results from the present methodology compared with the conventional near-surface models have substantiated that the present methodology provides high-resolution/ reliable velocity models for interpreting the low-velocity weathered layers.

Introduction

Developing the near-surface model is essential for land seismic data acquisition to understand the weathered layer changes and identify the optimum depth for placing explosives. Explosives should be placed below the low-velocity weathered layer for better penetration of seismic energy into the subsurface; subsequently, high-quality seismic data will be generated. Conventionally, near-surface velocity models were developed from the uphole data, which were acquired at regular intervals within the operational areas. This survey provides the thickness and vertical velocity of near-surface layers, including the weathered layer. This methodology uses firing charges at different depths in a drilled hole and measuring the arrival times at the surface with geophones at predefined locations. A plot was generated using arrival times against depths of charges. Different layers were identified by connecting lines of velocity breaks on the data points in the plot. Velocities of different layers, such as the weathered layer and sub-weathered layer, were extracted by calculating the inverse slope of each line. Due to cost-effective issues, we cannot acquire the uphole data at all shot hole locations. However, we interpolate the velocity and optimum depth information from the shot hole at one uphole location to the shot hole at another. Sometimes, this interpolation may not be accurate due to local geological conditions.

For a few decades, ambient seismic noise/passive seismic data has become a valuable tool for understanding shallow subsurface layers. The HVSR method can be more popular than other passive analysis methods in geological, geotechnics, and seismology studies (Gallipoli et al. 2004). The HVSR analysis requires three components of microseismic data, such as seismic noise, to generate an HVSR curve using the Fourier transform of three components of microseismic data. A low-velocity layer laid over on the hard layer (with high shear wave velocity, or Vs) is the assumption in interpreting HVSR curves. The seismic properties of the subsurface can be extracted using the Horizontal-to-Vertical Spectral Ratio (HVSR) analysis of microtremors/ambient noise at different frequencies (Gosar 2007). Shear wave velocity information can be determined based on the knowledge of fundamental resonance frequency and subsurface interfaces/ thickness. The HVSR analysis method provides a 1-D geological model regarding Shear velocity, Compressional velocity, density, and Poisson ratio. This method is a cost-feasible, reliable, and efficient tool for characterizing near-surface.

Many authors discussed the importance and advantages of HVSR analysis using passive seismic noise. Castellaro and Mulargia (2009a) used HVSR curves to characterize near surfaces at different locations by estimating shear velocities. Another study interpreted Microtremor HVSR curves by shear-wave velocity inversions of subsoil profiles (Castellaro and Mulargia 2009b). The HVSR of horizontal and vertical components of the microtremor are utilized to estimate ground-motion characteristics of 23 wards of Tokyo (Konno and Ohmachi 1998). A study summarized the application of the HVSR methodology in characterizing the subsurface at recorded locations (Xu and Wang 2021). (Cantwell et al. 2019) was discussed with many case studies on the application of the HVSR analysis for understanding the sand exploration and characterization of the near subsurface in the mining industry. It is a valuable methodology for estimating the thickness of soft layers laid over on the hard rock layers. However, it is suitable to identify the low-velocity layers (weathered layers) and sub-weathered layers using the horizontal and vertical components of microseismic data.

In this study, we used microseismic data to estimate shear wave velocities of near subsurface layers by analyzing the HVSR curves for developing the near-surface models. Developing the shear wave velocity was more precise than the compressional velocity, providing a more insightful analysis of low-velocity layer changes in the near subsurface. The present methodology modeled the near-surface changes of the weathered and sub-weathered layers through identified locations where already uphole data was acquired. Vertical shear velocity profiles were identified with depth at each location and interpolated for continuous 2D models. Finally, the present perspective's results were compared with conventional near-surface models generated from the uphole interpretation. The comparison has substantiated that velocity models developed by the present methodology provide more insightful information than conventional models. Acquiring microseismic data is practical, has low-cost feasibility, and has better results.

Methods and materials

The HVSR technique requires the recording of natural-seismic noise or energy vibrations using a seismometer, which records with three velocity meters for recording ground motion in directions of horizontal (north to south (x), east to west (y)) vertical (up to down (z)) between frequency ranges (0-250Hz) and over the long period of 20 min. Generally, the earth vibrates with minute amplitudes of microtremors less than several microns, and the period ranges from a tenth of a second to several seconds. Passive seismic data consists mainly of surface waves such as Rayleigh waves and Love waves generated from many sources such as winds, traffic movements, rains, anthropogenic shaking from roads, etc. Passive seismic energy is an external source that creates a seismic resonance between near-surface strata. We can identify this resonance in terms of the thickness and shear-wave velocity, and it is strongly amplified when layers have strong and sharp impedance contrast.

Trapping the seismic waves due to the lithological impedance contrast between geological layers is the fundamental phenomenon in the HVSR technique. Nogoshi and Igarashi (1971) introduced the analysis of HVSR methodology on passive seismic data and was popularized by (Nakamura 1989). Spectral ratio analysis between the Fourier spectrum of the microseismic data's horizontal (H) and vertical (V) components is significant for HVSR analysis. In a layered stratigraphy, the HVSR of passive data provides the resonance frequencies (f_r)of the subsurface layers due to the seismic waves trapped between layers where impedance contrast has existed. If the subsurface is a horizontal layered structure, body waves only involve trapping effects between the layers. Suppose the subsurface layers with lateral heterogeneities in thickness and velocity represent a 2D/3D structure. In that case, surface waves also involve the trapping phenomenon.

It provides the peaks in the H/V frequency curves. The resonance frequency (f_r) of a layer is estimated with the following equation, where the soft layer is laid over the hard layer.

$$fr = Vs/(4h) \qquad \text{………….} \quad (1)$$

f_r = Resonant frequency associated with boundary at soft layer and hard layer.

Vs =Shear wave velocity of the first layer h = Thickness

In a two-layered earth model, resonance frequency (f_0) can be used in estimating the overburden thickness (h) using the equation

$$h = Vs/(4f_r) \quad \ldots\ldots\ldots\ldots (2)$$

This method would be less effective without sufficient acoustic impedance contrast and in areas with reversal velocity (a high-velocity layer above a low-velocity layer). Modeling has suggested that the minimum overburden to bedrock impedance ratio should be 1:2 for the H/ V spectral ratio to be effective.

Data collection and processing

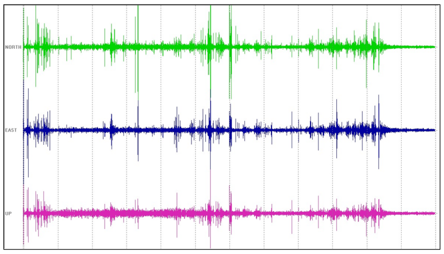


Figure 1: Three-component seismic data passive seismic acquired by microtremor at the location of Uphole 9.

Passive seismic data acquisition was conducted at 12 points in the vicinity of 12 uphole locations (where conventional uphole data was acquired) using the Tromino seismograph, which consists of three orthogonal electrodynamic velocity sensors for recording measurements in directions of horizontal (north to south (x), east to west (y)) and vertical (up to down (z)). At each point, passive seismic data were recorded for 20 minutes at a sample rate of 250Hz. Figure 1 shows the microseismic data acquired at uphole location no.9.

For processing and interpretation of three-component passive seismic data, the Grilla software was used. After recording the three-component passive seismic data at 12 locations, it requires to convert into the frequency-domain by Fourier transform, and the components are shown in the power spectrum. All records were smoothed with 5% smoothed and corrected for the sensor transfer function. The filtered three-component data were used for estimating HVSR from the ratio of the average values of both horizontal component values divided by the vertical values. Figure 2a shows the prepared HVSR curves from the microseismic data for interpretation along with amplitude spectra (Figure 2b).

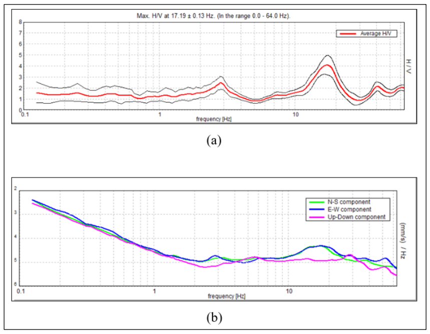


Figure 2: (a) Average HVSR curve of microseismic data; (b) Amplitude spectra of three components.

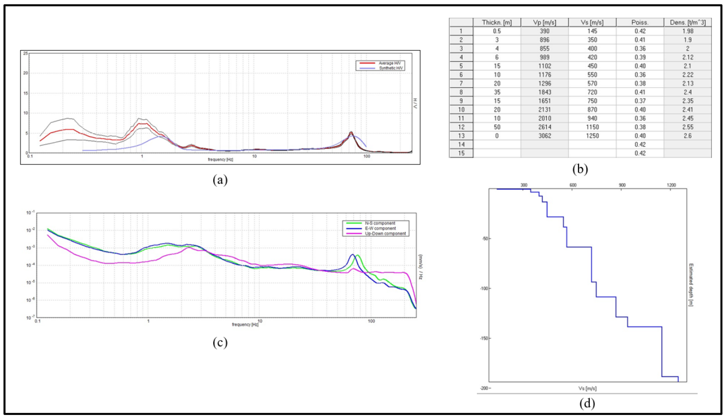
After preparing the HVSR spectrum, a subsoil model has to be generated with different layer thicknesses and velocities, such as shear and compressional velocities, which fit the recorded HVSR ratio. It means a synthetic HVSR curve has to fit with the recorded HVSR curve from microseismic data with a defined 1D subsoil model with various input parameters, such as velocities and densities.

Figure 3 shows the interpretation of HVSR curves and generating 1D subsoil model at the Uphole location 3. The blue color curve on the HVSR curves in Figure 3a indicates the synthetic HVSR curve that was generated from the subsoil model of different thicknesses with shear velocities, compressional velocities, density, etc. These velocities and density values in the subsoil model are the choice of the interpreter. The amplitude spectrum of each component has been shown in Figure 3c, which provides information about the frequency consistency of each component for each depth. The shear velocity profile of the subsoil model is shown in Figure 3d, which generates a suitable synthetic HVSR curve fitted with the HVSR curve of microseismic data (Figure 3a).

Results and Discussions

This study has generated a near-surface velocity model by generating the 1D geological/ velocity models from acquired microseismic data at 12 locations. Passive seismic data were collected at 12 locations for developing the 1D velocity models/geological models confined up to a depth of 60m. In the same locations, the uphole data were also collected and interpreted. An interpolated near-surface model was generated from the velocity profiles of Uphole data interpretation and another from the interpretation of microseismic data. The conventional methodology involves measuring the arrival time after the firing of charges at different depths in a drilled hole of about 60m. The first break was picked and analyzed to identify layers with similar slopes on the plot of arrival times versus depths where the charge was blasted. The interpretation of each Uphole was interpolated for the layer model. In the same way, a near-surface model was generated from the V_S profiles obtained by interpreting the HVSR curve at each station of measurement.

Figure 4 shows the results (V_S profiles) of the HVSR analysis of microseismic data at the different Uphole locations. The results from the HVSR interpretation provided the minute thickness of layers with different velocities at the measurement locations. From knowledge of Geological formation on the side southwest of the river having the low-velocity sand layer between two hard rock formations in the range of depth 7m-14m. The high-resolution V_S profile at each measuring station on the side of the southwest to the river was identified. The same results are not visible in the conventional Uphole survey.



	Thickn. [m]	Vp [m/s]	Vs [m/s]	Poiss.	Dens. [t/m^3]
1	0.5	390	145	0.42	1.98
2	3	896	350	0.41	1.9
3	4	855	400	0.36	2
4	6	989	420	0.39	2.12
5	15	1102	450	0.40	2.1
6	10	1176	550	0.36	2.22
7	20	1296	570	0.38	2.13
8	35	1843	720	0.41	2.4
9	15	1651	750	0.37	2.35
10	20	2131	870	0.40	2.41
11	10	2010	940	0.36	2.45
12	50	2614	1150	0.38	2.55
13	0	3062	1250	0.40	2.6
14				0.42	
15				0.42	

Figure 3: Interpretation of HVSR curves of Microseismic data.

	Compressional Velocities (V_P) from Uphole (m/s)			**Estimated Shear Velocities (V_S)from Uphole (m/s)**			**Average Shear Velocities (V_S) from HVSR Analysis (m/s)**		
UH-NO	**V_P1**	**V_P2**	**V_P3**	**V_S1**	**V_S 2**	**V_S 3**	**V_S 1**	**V_S 2**	**V_S 3**
UH-1	1320	5812		516	2270		481	2056	3560
UH-2	1835	4278	5803	717	1671	2515	614	1761	2423
UH-3	934	2894	5102	365	1130	1322	289	990	1200
UH-4	920	3748		359	1464		312	1200	1986
UH-5	779	1605	5677	304	627	2117	345	610	2054
UH-6	766	2911	5694	299	1137	2217	368	951	2161
UH-7	1169	3934	5967	457	1537	2219	431	1423	2391
UH-8	1621	4592		633	1794		734	1622	2566
UH-9	1806	2927	3976	705	1143	1351	689	1011	1678
UH-10	1371	5603		536	2189		612	2213	3245
UH-11	1262	5633		493	2200		434	2089	3567
UH-12	860	4612		336	1802		380	1701	2765

Table 1: Comparison of Shear velocities estimated from both methodologies at all measured locations.

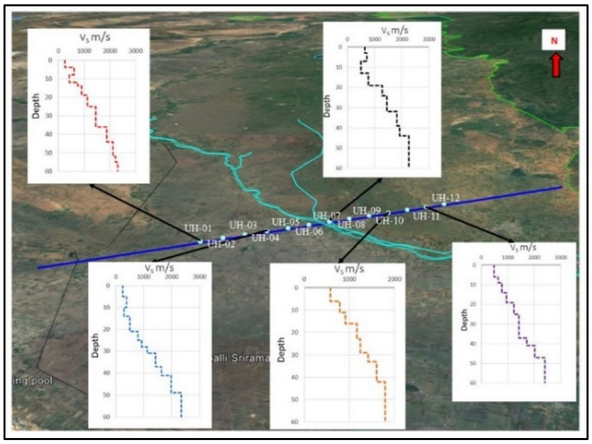


Figure 4: Shear Wave Velocity Profiles (V_S) obtained from HVSR analysis at different stations.

The V_S values were estimated for the case of three layers from the V_P estimated by interpreting the Uphole data (Table 1) (Castagna, Batzle, and Eastwood 1985). The relationship between velocities and the Poisson ratio is used to estimate the V_S values. Based on the microseismic study, we have considered V_P/V_S ratio as 2.56 based on Poisson ratio value 0.40 for the present study area

These V_S values are compared with V_S values obtained from the HVSR analysis. The results were averaged for the three-layer case equal to the Uphole interpretation. The trend of all V_S values from both methodologies followed the same trend of changes, and it was comparable. This comparison indicates that the proposed technology has given satisfactory results as the uphole interpretation and provides higher resolution results than the conventional methodology. With the comparison of conventional Uphole data analysis, HVSR analysis provided more layers of information.

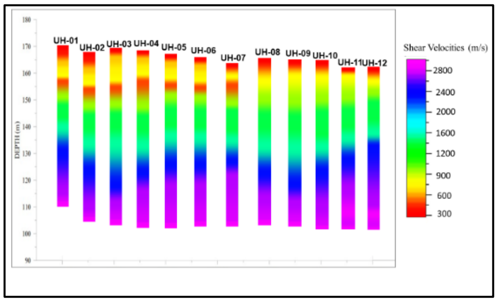


Figure 5: RMS velocity profile (V_S) at microtremor stations reference to elevations.

Figure 5 shows the RMS velocities profiles that were developed from interval velocities of HVSR interpretation at each station (at Uphole locations) (Sain and Kaila 1996). It was more interpretable than the conventional analysis that only provided information about macro layers, but the present methodology also provides the very minor layer's velocities variation. The RMS velocities trend shows that the low-velocity layer (V_S) is observed and varies from 8m to 14m on the southwest side of the river due to unconsolidated sand. The conventional near-surface model was limited in this interpretation. Figure 6 compares the near-surface layer models developed from the Uphole data analysis and HVSR interpretation of passive seismic data. These models of both methodologies are developed in reference to elevations.

The layer model of the present methodology had more layers of information and provided critical low-velocity layer information than the conventional near-surface model information on the side of the southwest of the river. The first layer variations in conventional Uphole modeling are almost comparable with the present methodology layer modeling (Red & Sky Blue at 160m in Figure 6b). Similar trend variations were observed in the second layer of the conventional model with the comparison of the present methodology (Orange color at 140m).

The results have substantiated that the methodology based on HVSR analysis of microseismic data can provide reliable near-surface information such as velocities, low-velocity layer changes, and variations in geological layers. It can be helpful in the identification of weathered layers and sub-weathered layers and the identification of optimum depth for placing the explosive as an alternative technique for conventional Uphole methodology.

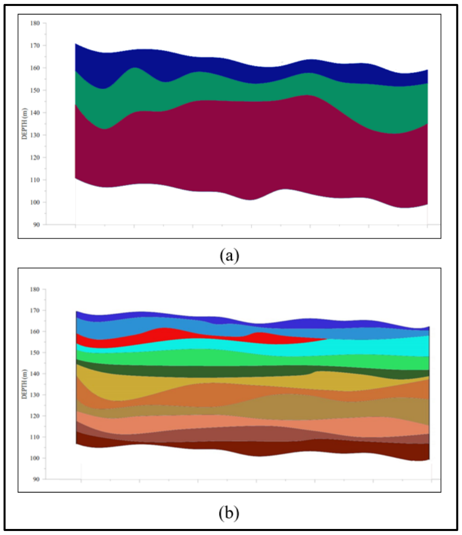


Figure 6: Comparison of near-surface layer models: (a) velocity model from Uphole data; (b) velocity model from Microseismic data;

Advantages and disadvantages

Advantages:

- High-resolution layers can be modeled.
- No source is required. Passive noise was enough
- Easy to interpret
- Low-cost acquisition than the Uphole survey, and results are also better than the Uphole interpretation.

Disadvantages:

- HVSR analysis needs to take more care while dealing with Hard-soft formation
- Identification of initial velocities for fitting the synthetic curve is complex.
- With the support of the seismic refraction technique, the present methodology provides more significant results.

Conclusions

This study used HVSR analysis to develop the near-surface model for identifying weathered and sub-weathered layer changes. We have collected passive seismic data at 12 locations where the Uphole survey was conducted. HVSR analysis was applied to the passive data and a V_S profile with depth at each station. From these velocity profiles (V_S), we have estimated 1D RMS velocities to understand minor changes in near-surface velocities at each location. From these, RMS velocities are interpolated, converted into a layer model, and compared to the model generated from conventional Uphole data. The results proved that HVSR analysis provided high-resolution models and is competitive with existing methodology.

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