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Application of Microtremor Analysis for Soil Characterization in Urban Areas

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ABSTRACT

Landslides pose a significant threat to safety and infrastructure in Malaysia, exacerbated by its tropical climate and rapid urbanization. Traditional assessment methods are often impractical for frequent monitoring due to their destructive nature. This study explores the application of the Horizontal-to-Vertical Spectral Ratio (HVSR) method, integrated with Multichannel Analysis of Surface Waves (MASW), for subsurface characterization and slope stability evaluation. Key findings include shear wave velocity profiles from MASW (180–250 m/s at 0–10 meters depth) and HVSR (147 m/s at 0–5 meters), which are crucial for assessing soil stiffness and seismic hazards. The subsurface was stratified into four zones based on Vs and SPT-N values, providing insights into soil strength and compaction. The HVSR analysis revealed fundamental resonance frequencies indicative of subsurface layer thickness and stiffness. This study validates the effectiveness of HVSR in complementing traditional methods, offering a rapid and cost-effective solution for landslide risk management. The results contribute significantly to enhancing geotechnical engineering practices in Malaysia and similar regions, highlighting the potential for widespread adoption of non-destructive techniques in landslide risk assessment and mitigation strategies.

Keywords:
Geotechnical investigation; HVSR; peak amplitude (A_o); resonance frequency

1. Introduction

Malaysia, situated in Southeast Asia, experiences a tropical climate characterized by high humidity and rainfall, which, combined with its diverse topography, particularly the extensive hilly and mountainous terrains like the Cameron Highlands, contributes to the increasing incidence of landslides. Between 1993 and 2019, Malaysia recorded 49 landslides, a significant rise from the single reported incident prior to 1993 at Ringlet, Cameron Highlands [1]. This heightened frequency underscores the need for proactive slope stability evaluations. Besides climatic and topographic

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factors, rapid economic development and urbanization, especially in hilly regions, exacerbate landslide risks [2]. Extensive deforestation and land clearing for residential, agricultural, and commercial purposes compromise the natural stability of slopes, while infrastructure development through slope modification and artificial embankment construction can lead to ground instability [3]. In this context, thorough slope stability assessments are crucial for hazard detection and prevention. However, traditional methods like the Standard Penetration Test (SPT) and soil borehole drilling, although widely used in geotechnical engineering to establish subsurface conditions, are impractical for frequent use on unstable slopes due to their time-consuming and destructive nature [4]. To address these limitations, rapid and non-destructive testing methods are essential for initial site investigations and long-term monitoring. Techniques such as the Horizontal-to-Vertical Spectral Ratio (HVSR) method offer a viable alternative, providing a non-destructive, cost-effective solution for subsurface characterization and continuous slope monitoring.

2. Literature Review

2.1 Landslide Types, Hazards, and Regional Impact

Landslide, which refers to movement of man-made materials, Earth, or rock by falling, flow, or sliding by gravity, is a major hazard in Malaysia [5]. Rotational landslides involving curved planes of failure in cohesive materials including clay tend to be caused by heavy rains, as in the 2014 Bukit Antarabangsa landslide that involved wide property destruction and loss of life. Translational landslides in planar planes like bedding planes or interfaces of soils are prone to small vertical movement and extensive horizontal movement, as in the 1993 Pantai Remis that resulted in uncontrolled mining [6]. Steep and rainfall-susceptible slopes like that of Cameron Highlands are seriously prone to flows of debris (watery, fast-flowing mixture of fragmentary material and clay) and slow flows of earth, the latter causing terracing upon long-term inundation. These are supplemented by Malaysia's tropical climate of high annual rainfall and humidity and man-made causes like deforestation and topographic change. Of 7,305 landslides reported across the country between 1961 and 2022, over 50 lives were lost, and acute economic loss was incurred in the last decade [7]. Among the worst in occurrence was the 2017 Bukit Kukus, Penang landslide caused by heavy rains and killing seven and revealing system faults in schemes of crisis management [8]. Despite the fact that landslide occurrence in Malaysia is less compared to very susceptible nations like the United States or Switzerland, lack of engineering controls in hilly tracts like that of the Genting Highlands continues to perpetuate instability [9]. Alongside their direct destruction, landslides facilitate long-term environmental degeneration, displacement of dwellers, and secondary hazards like post-earthquake collapse of slopes, hence the need for efficient measures in mitigation in the struggle against this multi-aspect hazard.

2.2 Introduction to Passive Seismic

Passive seismic methods are widely preferred in geophysical application due to their cost efficiency, non-destructive nature, and capacity to generate useful subsurface data in the form of ambient seismicity. In contrast to man-made seismic wave-based active seismic methods involving controlled or explosive or vibroseismic sources, passive seismic methods involve naturally occurring seismicity. Environmental ambient noises, microtremors, and environmental background motions generate such seismicity [10]. As passive seismic studies are devoid of any direct mechanical ground disturbance, in cities, in environmentally sensitive regions, or in regions where normal active seismic methods are impractical or banned by code or logistics considerations, passive seismic methods are particularly beneficial. Subsurface condition assessment of infrastructure projects, e.g., bridge, highway, or high-rise buildings, is one important application of passive seismic methods. Passive seismic methods also find crucial application in seismic hazard assessment and local seismic effects in seismic regions, allowing geologists and engineers to better comprehend how ground motion might affect buildings and topographies.

2.3 Horizontal-to-Vertical Spectral Ratio (HVSR) Method in Geophysics

Horizontal-to-Vertical Spectral Ratio (HVSR) is subsurface structure identification by analysis of seismic signals. It calculates the horizontal-to-vertical ground motion components' ratio of ambient oscillations. Nogoshi and Igarashi first proposed it, then Nakamura expanded it in [11]. Utilizing the relationship of seismic wave frequencies and mechanical subsurface parameters in calculating a site's fundamental resonance frequency (f_0), i.e., one of the primary parameters in natural frequency estimation and in impedance contrast estimation, the method records the ambient noises by a three-component broadband seismograph, records' length varying between minutes to several hours according to desired (f_0). Data procession includes windowing records in segments of time (statistically optimized for stability) and converting signals to the frequency domain [12]. Summed are the horizontal components, and the curve of HVSR is derived by division of their Fourier spectra of amplitude by that of the vertical component [13]. Its clear peak is (f_0), which is confirmed by iterative analysis of all segments, i.e., individual HVSR provides fast, low-cost subsurface data, it is often combined in conjunction with methods like electrical resistivity tomography (ERT) and shearing wave velocity profiling in improving stratigraphic reliability. For instance, Parolai *et al.,* [14] reported agreeing well of HVSR-calculated (f_0), thickness of sediments, shearing wave speeds when cross-validated v/s borehole data, highlighting in that it can prove useful in geotechnical application.

2.4 Frequency Values of Subsurface

Seismic waves cause a material layer to vibrate at its natural resonance frequency when they match that frequency. This resonance depends on the layer's thickness, density, and shear wave velocity [15]. The fundamental frequency (f_0) is determined by:

$$f_0 = \frac{V_s}{4h} \tag{1}$$

whereby the
f_0 = fundamental resonant frequency of a specific layer
V_s = shear wave velocity
h = thickness of the layer

Each subsurface layer has a unique resonance frequency based on its properties. Different frequency ranges correspond to specific soil compositions, conditions, and thicknesses [16]. Table 1 categorizes these frequency ranges accordingly.

Table 1
Basic frequency ranges and the subsurface materials description

Frequency range	Subsurface description
Less than 1.0 Hz	A group of unconsolidated sediment (loose, soft soil) that is quite deep
1.0 Hz to 2.0 Hz	Alluvial sediments, both coarse and thick. Unconsolidated deposits of sand and clay tend to be quite loose
Less than 4.0 Hz	Finely grained soil with a comparatively thin layer
More than 5.0 Hz	Materials with a coarse granularity, deposits of volcanic ash, and artificial deposits. A remarkably thin layer of consolidated, well-compacted sediments
Lower than 12.0 Hz, greater than 10.0 Hz	Hard rocks, basement

2.5 Amplification Index and Shear Wave Velocity of Soil Condition

The Amplification Index (AI) measures how much subsurface conditions and soil amplify seismic waves. This index is crucial for assessing seismic sensitivity across different soil types and evaluating seismic hazards in urban planning and construction. Various studies worldwide have established amplification index ranges based on different soil conditions.

Several factors influence the amplification index, like resonant frequency. Different soil types—such as rock, sand, gravel, and clay—amplify seismic waves to varying degrees. Thicker soil layers generally lead to higher amplification, and lower shear wave velocity (V_S) is often associated with greater amplification factors [17].

For instance, studies in Indonesia indicate that amplification is due to layers of soft clay of considerable thickness and that it intensely amplifies seismic hazard in certain regions [18]. To be aware of and quantify the amplification index better helps planners and engineers to better assess and mitigate seismic hazards.

Shear wave velocity or V_S is a key parameter in both seismology and geotechnical engineering that controls seismic wave amplification and dynamic soil behavior [19]. It is the velocity of the shearing wave in the ground and gives information on how stiff the ground is and how efficiently it can transmit seismic wave energy.

There exist varying parameters of shears' velocity. Soils of sand, clay, gravel, and rocks have varying V_S values, and denser compacted soils have higher velocities [20]. Its value also depends upon water content, and higher water content reduces V_S. Conditions of high loading and prior stress also change V_S, which affects the stiffness of soils. Temperature also changes the physical parameters of soils, resulting in varied V_S. These parameters are needed in order to compare seismic hazards and site conditions properly.

2.6 Correlation of Shear Wave Velocity with SPT-N

Several studies have examined the relationship between SPT-N values and shear wave velocity (V_S) using various seismic survey methods. It is indicated that there is a direct relationship between V_S and SPT-N values, and it is also considered that the use of seismic wave velocity data will increase the interpretation of subsurface conditions for engineering purposes [21]. NEHRP also classifies the sites based on both Vs and SPT-N. NEHRP classifies the sites as given in Table 2, where it classifies the soils in terms of average Vs and SPT-N up to 30 meters deep [22].

Table 2
NEHRP site classification system

Class	Description	V_s, m/s	SPT-N
A	Hard rock	>1,500	
B	Firm and hard rock	760 - 1500	
C	Dense soil and soft rock	360–760	N > 50
D	Dense to medium soil	180–360	15 < N < 50
E	Medium to soft soil	<180	N < 15

3. Methodology
3.1 Data Acquisition

The data was collected in Cheras area. The geological formation is primarily composed of acid-intrusive granitic rock. Seismic data was collected using a three-component seismometer as shown in Figure 1 placed on the studied slope, to measure ambient vibrations. The sensor orientation was verified before recording to ensure accuracy. Data was recorded for 60 minutes to capture stable signals.

Fig. 1. Seismometer connected to power supply

For additional comparison of results, Multichannel Analysis of Surface Waves (MASW) is also carried out based on Figure 2. MASW field survey procedure is also the same as that for seismic refraction survey with the exception that one shot alone is required into the geophone array.

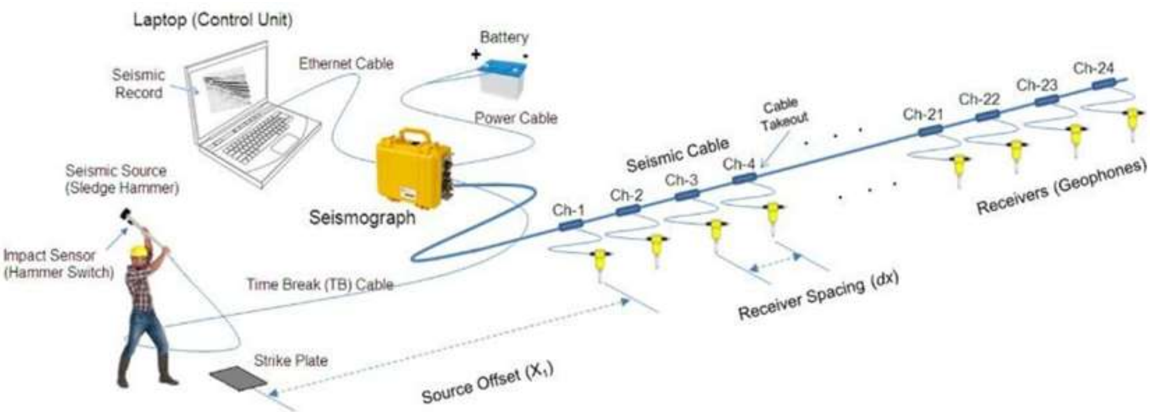

Fig. 2. Schematic description of fieldwork setup with typical generation of seismic wave

The geophone array is laid in a straight line at regular interval as adopted in seismic refraction survey and the generation of impulse is produced using a sledgehammer as shown in Figure 2.

3.2 Data Processing

Seismic data processing refines raw seismograph signals to enhance signal quality and extract subsurface characteristics through sequential steps: noise removal, baseline correction, and instrument response compensation. Ambient noise—low-frequency disturbances (e.g., wind, traffic) and high-frequency interference from machinery—is mitigated via band-pass filters, while baseline correction centers data to eliminate drift. Deconvolution techniques further remove instrument-induced distortions using predefined response functions. Figure 3 illustrates this workflow across eight measurement points (Points 18–95), with Point 18 serving as the representative case study.

Fig. 3. Point of recorded data

Figure 4 displays its raw HVSR waveforms (vertical [Z], north-south [N], and east-west [E] components), capturing ambient vibrations for resonance frequency analysis. Critical to this process is segmenting the raw signal into noise-free intervals (colored windows in Figure 5), which are analyzed in the frequency domain after applying a Konno-Ohmachi window to minimize spectral leakage. The windowed segments undergo Fast Fourier Transform (FFT) to compute amplitude spectra, enabling Horizontal-to-Vertical Spectral Ratio (HVSR) curve derivation. A uniform 25-second window length ensures consistency across all points, balancing frequency resolution and statistical reliability.

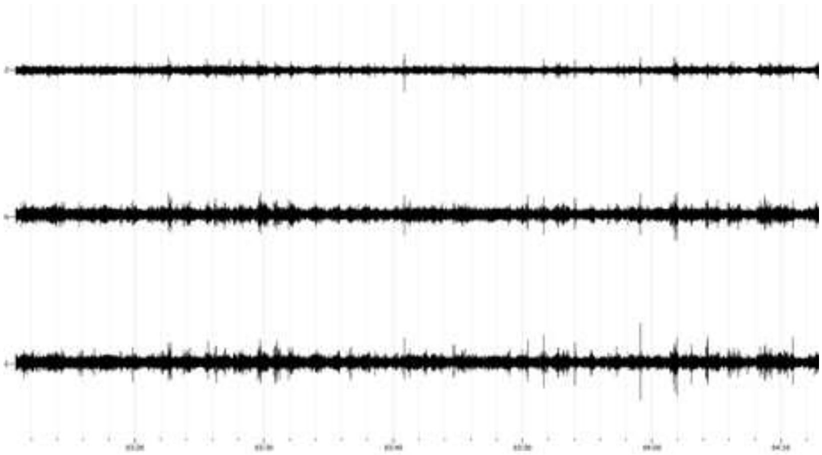

Fig. 4. Raw data of Point 18

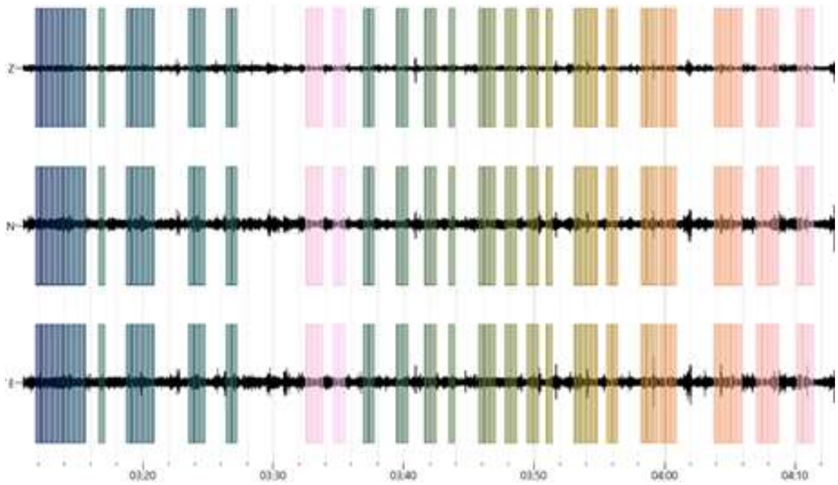

Fig. 5. Filtered data of point

3.3 Conversion Shear Wave Velocity to SPT-N

The following equation between V_s (m/s) and SPT-N values was proposed for the all soil categories. This equation was prepared based on the data collection conducted by Jusoh *et al.,* [23]. According to Jusoh *et al.,* [23] the equation was prepared based on the data collection conducted around Peninsular Malaysia. The correlation indicates a strong relationship with conventional SPT-N.

For all soil types:

$$V_s = 85.385N^{0.3516} \quad (2)$$

4. Results and Analysis

Shear wave velocity (V_S) was determined using Multichannel Analysis of Surface Waves (MASW) and the Horizontal-to-Vertical Spectral Ratio (HVSR) technique. These geophysical methods were employed to evaluate subsurface soil stiffness and its variation with depth. The results offer critical insights into stratification and the mechanical behavior of subsurface layers.

The Figure 6 shows the inversion results of HVSR, highlighting key subsurface parameters such as shear wave velocity V_S with depth. The V_S profile, a crucial parameter for assessing soil stiffness and seismic site response. Figure 7 classifies subsurface materials based on shear wave velocity (Vs) and

Standard Penetration Test (SPT-N) values obtained from MASW. The left panel illustrates Vs distribution, categorizing the subsurface into four zones: soft/firm (0–200 m/s), stiff/very stiff (200–300 m/s), hard/dense (300–400 m/s), and weathered rock (>400 m/s). These classifications help determine subsurface stiffness and engineering properties.

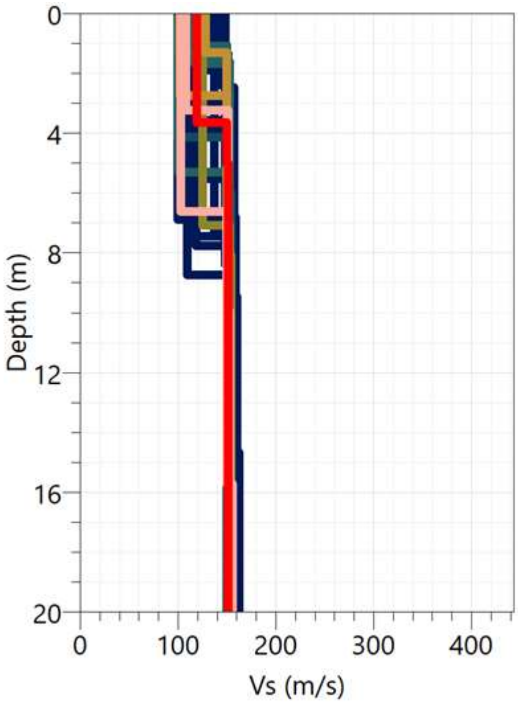

Fig. 6. HVSR inversion at point 18

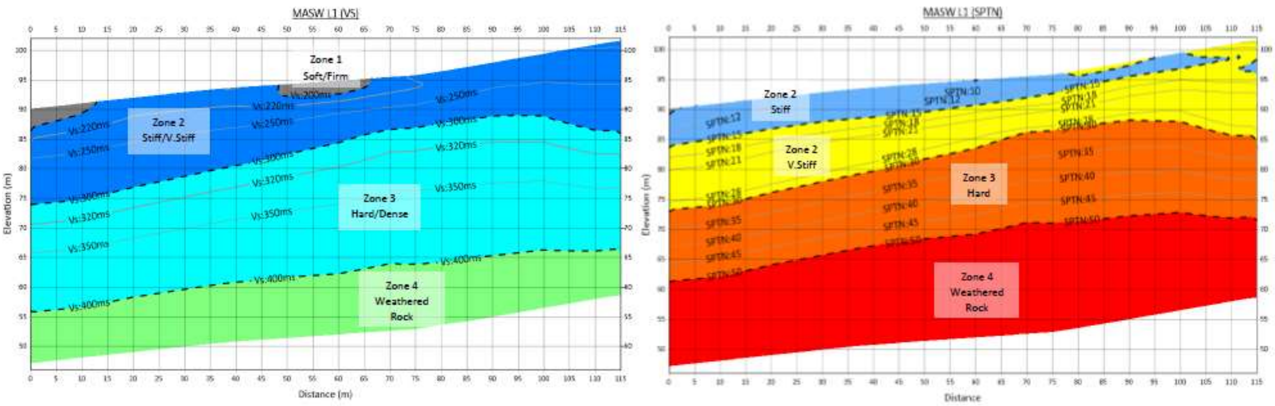

Fig. 7. Shear wave velocity and SPT-N profile from MASW

The right panel presents corresponding SPT-N values, offering additional geotechnical insights into soil strength and compaction. Lower SPT-N values (N < 15) indicate very soft to firm soils, while higher values (N > 30) represent stiff to hard zones. The transition from soil to rock is distinct, marking a progressive shift from weathered rock to competent material. These findings are critical for geotechnical site characterization, foundation design, and seismic hazard assessment.

Table 3 compares shear wave velocity (Vs) values derived from Multichannel Analysis of Surface Waves (MASW) and Horizontal-to-Vertical Spectral Ratio (HVSR) methods for depths of 0–20 meters, providing insights into subsurface stiffness and method consistency.

Table 3
Shear wave velocity obtained

Depth (m)	Shear Wave Velocity, Vs (ms^{-1})	
	MASW	HVSR
0-5	180 - 220	147
5-10	220 - 250	160
10-15	250 - 320	162
15-20	300 - 350	223

At 0–5 m, MASW indicates Vs values of 180–220 m/s, classifying the layer as soft to firm soil. HVSR estimates Vs at 147 m/s, slightly lower due to its reliance on empirical relationships, which may underestimate Vs compared to surface wave methods. In the 5–10 m range, MASW shows an increase to 220–250 m/s, indicating stiffer soil, while HVSR records 160 m/s, following the overall trend but with a greater discrepancy due to differences in wave propagation mechanisms.

The Horizontal-to-Vertical Spectral Ratio (HVSR) analysis provides critical insights into the subsurface conditions along the survey line, complementing the findings from the Multichannel Analysis of Surface Waves (MASW). The fundamental resonance frequency (F_0) measured in hertz (Hz), serves as an indicator of subsurface stiffness and layer thickness, with lower frequencies corresponding to thick, soft sediment deposits and higher frequencies representing denser, more compacted materials. Additionally, the peak amplitude (A_0) reflects seismic impedance contrasts, where higher values indicate significant material transitions, such as the soil-bedrock interface.

The HVSR results presented in Table 4 indicate that points with F_0 values between 2 and 5 Hz, such as Points 18, 29, and 40, correspond to fine-grained soils with relatively thinner layers. This observation aligns with the MASW findings, which classify these layers as soft-to-stiff soil deposits. The lower shear wave velocity (V_s) associated with these points suggests the presence of clayey or silty materials. In contrast, points with F_0 values between 5 and 10 Hz, such as Points 73 suggest the presence of course-grained materials, volcanic ash deposits, or compacted manmade fill [24]. The MASW data further supports this interpretation by indicating denser soil and weathered rock layers, which typically exhibit higher V_s values.

Table 4
Resonance frequency and peak amplitude along survey line

Point	Resonance frequency, F_0 (Hz)	Peak amplitude, A_0
18	3.955350	4.865590
29	4.010645	3.740900
40	5.161600	5.013870
73	6.873630	7.657450

The variations in the A_0 across the different sites are indicative of probable stratigraphic variations, while the high contrasts in impedance identify the transition of soils or contact between soils and bedrocks. Large property contrasts are indicated by high values of A_0, which translate to large subsurface changes or a harder subsurface. These variations are critical in the subsurface heterogeneity characterization as well as seismic site characterization.

The figure on the left (Figure 8) shows the spatial amplification distribution of ground motion where the ground motion amplification changes spatially across different sites. Yellow to red regions of high amplification value are regions of strong amplification due to soft ground material. Blue to green-colored regions of low amplification value are bedrocks or stiff soils that experience little amplification. Local site conditions themselves decide the change in amplification. Low-velocity shearing wave soft sediments greatly amplify ground motion. Amplitude differences are pertinent in seismic hazard assessment in the sense that regions of high-amplitude value are susceptible to strong shaking of the ground in earthquakes, having effects on infrastructure and built environments. These amplification distributions are important in the sense that seismic risk mitigation and engineering design may be better planned in earthquake-prone regions.

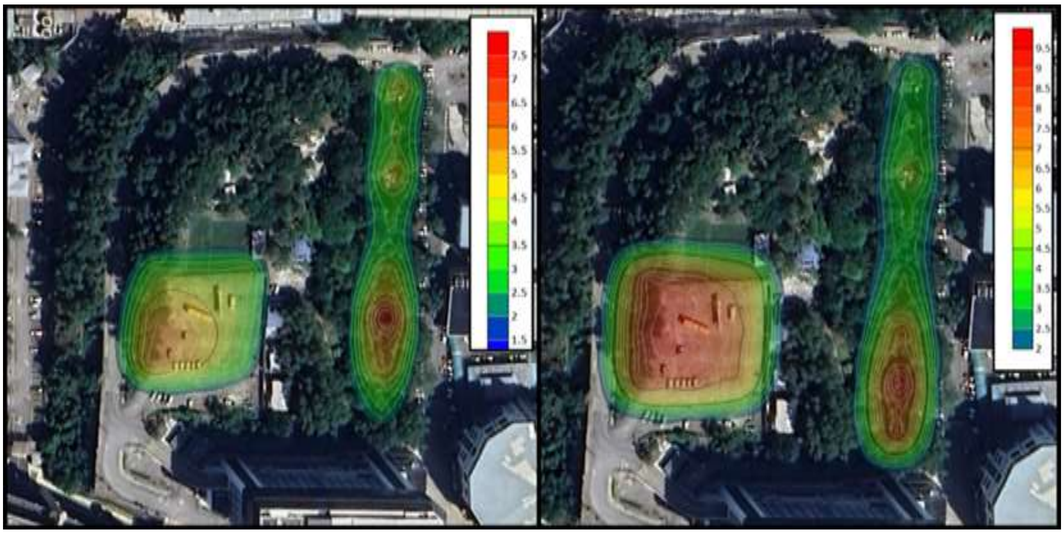

Fig. 8. Spatial variation of amplitude (left) and frequency (right)

Frequency and amplitude maps are significant in site response analysis, each playing different roles. Amplitude maps indicate ground motion amplification levels, defining regions where seismic motion is increased due to softer subsurface materials. Frequency maps, by contrast, indicate stiffness and subsurface thickness of layers by displaying the dominant resonance frequencies of the site. Both parameters enable geophysicists and engineers to study seismic site effects, identify potential hazards, and design buildings that will withstand local ground motion characteristics. Integration of frequency and amplitude data yields a better site-specific seismic behavior, enabling successful earthquake-resistant design and hazard mitigation strategies.

5. Conclusion

The increasing prevalence of landslides in Malaysia, exacerbated by climatic, topographic, and anthropogenic factors, necessitates innovative approaches to slope stability assessment. This study explored the application of the Horizontal-to-Vertical Spectral Ratio (HVSR) method as a non-destructive and cost-effective alternative for subsurface characterization and slope monitoring, addressing the limitations of traditional geotechnical approaches. The primary objective was to evaluate the feasibility of HVSR for assessing subsurface conditions in landslide-prone areas. Ambient vibration data were collected using three-component seismometers across eight measurement points, with results validated against Multichannel Analysis of Surface Waves (MASW). HVSR provided resonance frequency (f_0) data, while MASW offered shear wave velocity (V_s) profiles. The integration of these methods ensured robust subsurface characterization. The study revealed critical insights into subsurface conditions:

i. Resonance Frequencies (f_0): HVSR identified f0 values ranging from 1.2 Hz to 5.6 Hz across surveyed points, indicating variations in subsurface stiffness and layer thickness. Lower frequencies corresponded to thicker, softer sediments.

ii. Shear Wave Velocity (V_s): MASW-derived Vs values ranged from 180–220 m/s at depths of 0–5 m (soft to firm soils) and increased to 220–250 m/s at depths of 5–10 m (stiffer soils). HVSR-derived V_s values were slightly lower (e.g., 147 m/s at 0–5 m), reflecting its reliance on empirical models.

iii. Material Classification: Subsurface materials were categorized into four zones: soft/firm (V_s < 200 m/s), stiff/very stiff (200–300 m/s), hard/dense (300–400 m/s), and weathered rock (V_s > 400 m/s). These classifications aligned with Standard Penetration Test (SPT-N) values, where lower SPT-N (<15) indicated soft soils and higher values (>30) denoted stiff zones.

This study underscores the efficacy of HVSR as a rapid and reliable tool for geotechnical investigations in landslide-prone regions. Its ability to detect fundamental resonance frequencies and seismic impedance contrasts provides valuable insights for initial site assessments and long-term monitoring. When combined with MASW, HVSR enhances stratigraphic accuracy, offering a practical solution for slope stability evaluations in resource-constrained settings. The findings have significant implications for landslide risk management in Malaysia. The integration of passive seismic methods into geotechnical practice can improve hazard mitigation strategies by providing cost-effective, non-invasive subsurface data. Future research should focus on refining empirical models for Vs estimation and expanding the application of hybrid methodologies to diverse geological settings. This study contributes to advancing slope stability assessment techniques, bridging the gap between traditional geotechnical methods and modern non-invasive approaches. The adoption of HVSR and complementary techniques has the potential to transform landslide risk management practices globally, particularly in regions with similar environmental and developmental challenges. Note that this study aims to promote geophysical surveys as a supplementary tool to conventional methods. The authors believe that conventional methods remain a relevant and reliable approach for delineating the subsurface profile.

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