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Research paper

SITE CHARACTERIZATION OF STRONG MOTION STATIONS IN NORTH MACEDONIA

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Abstract

This study focuses on the site characterization of strong motion stations in North Macedonia using H/V spectral ratio analysis of both microtremor measurements and recorded earthquake data. It presents a methodology for calculating the H/V spectral ratio from earthquake recordings, with results compared to those obtained from microtremor measurements (available for most stations) to assess consistency and reliability. Currently, thirteen strong motion stations are operational across the country, with additional data available from thirteen non-operational stations. Several sites have been previously investigated through geophysical surveys and borehole geotechnical studies, which are also utilized in this study for comparison with the newly conducted H/V analyses. The analysis emphasizes the influence of local site conditions on recorded ground motions and identifies potential site amplification effects. These findings will serve as a basis for defining appropriate frequency ranges in the calculation of the high-frequency decay parameter, kappa (κ), for the territory of North Macedonia. Future work will explore the potential correlation between the fundamental site frequency and the site-specific attenuation component (k_0) of kappa, aiming to improve the understanding of local site effects. These insights could contribute to the refinement of site classification schemes for the next generation of Eurocode 8.

Key words: *Earthquake Recordings, Horizontal-To-Vertical Spectral Ratio (H/V), Site Effect, Site Response, Strong Motion Stations*

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1. INTRODUCTION

Strong motion play a crucial role in seismic hazard assessment, emergency response, damage evaluation, the improvement of building codes, the development and calibration of ground motion prediction equations (GMPEs), and for the advancement of further research studies. Subsurface conditions at the seismic station locations significantly influence the amplification and attenuation of seismic waves, affecting structural responses and potential damage. Understanding the site effects and their correlation with earthquake damage is crucial for site classification in accordance with seismic design codes requirements.

Various parameters are used to classify site conditions, with the most commonly adapted being the average shear wave velocity in the upper 30 meters of soil (V_{S30}). The current EC8 code [1] defines five site classes for soil classification based on V_{S30} values: A (>800m/s), B (360-800 m/s), C (180-360 m/s), D (<180 m/s), E (-).

V_{S30} *can be determined* through geophysical and borehole geotechnical investigations, as well as using horizontal-to-vertical spectral ratio (H/V) analysis. H/V analysis of microtremor or earthquake data enables estimation of the fundamental site frequency (f_0), and provides insights into local site effects, soil resonance characteristics, and amplification.

The low-cost microtremor horizontal-to-vertical (H/V) method, introduced by Nogoshi and Igarashi 1970 [2] and popularized by Nakamura 1989 [3], assumes that horizontal ground motions are amplified around the fundamental frequency, while vertical motions remain relatively unaffected [4]. It has been widely applied in seismic microzonation studies to assess local site response, resonance frequency of soft sediments, and spectral H/V peak amplification, which reflects the impedance contrast between soft sediments and bedrock [5,6]. If a H/V curve exhibits a clear peak, the frequency corresponding to the first dominant peak ($f_{0H/V}$) can be considered as the fundamental resonant frequency of the site (f_0). While the ability of H/V to accurately retrieve f_0 is widely accepted, the interpretation of the amplitude of the H/V curve remains a subject of debate. [5,7,8].

Studies confirm that this method is effective for both microtremor and strong ground motion data, yielding consistent results across different datasets [7,9,10,11]. Conducting extensive H/V data analysis recorded across an entire seismic network, combined with f_0 estimation, enhances site response analysis and helps identify potential local effects. Recent research [12-15] suggests that integrating both f_0 and V_{S30} provides a more comprehensive understanding of site response.

In addition to V_{S30} and f_0, the high-frequency attenuation parameter kappa (κ) - particularly its site-specific component k_0 - is increasingly accepted as a key indicator of site effects. Kappa describes the decay of spectral amplitudes at high frequencies and reflects the damping characteristics of near-surface materials. Accurate determination of κ requires detailed knowledge of the subsurface conditions beneath each station and the ability to avoid frequency ranges influenced by site resonances, which can bias kappa estimates.

In this study, earthquake acceleration data from the UKIM-IZIIS strong motion network in North Macedonia were analyzed. The research begins with an overview of the study area and instrument placement. It then outlines the site characterization methods and available data, followed by an analysis of microtremor measurements and H/V analysis using earthquake data. Finally, the study presents and discusses the results on fundamental site frequency (f_0) and V_{S30}, exploring their correlation and drawing appropriate conclusions for future applications in kappa calculation and correlation to the site-specific component k_0.

2. STRONG MOTION NETWORK

IZIIS strong motion network was established in 1972 as part of the Yugoslavian seismic network. Initially, the network consisted of analog instruments, which were later digitalized. Currently, there are seventeen active strong motion stations. Figure 1 shows the station locations and names where accelerometric data are available, including both active and inactive stations. All instruments operate at a sampling rate of 200 Hz. The accelerometers are installed in free-field conditions, in the basements of small buildings, or on the ground floor and are presented with different colors in Figure 1. Regarding soil characteristics, the instruments are placed on bedrock and characteristic soil types.

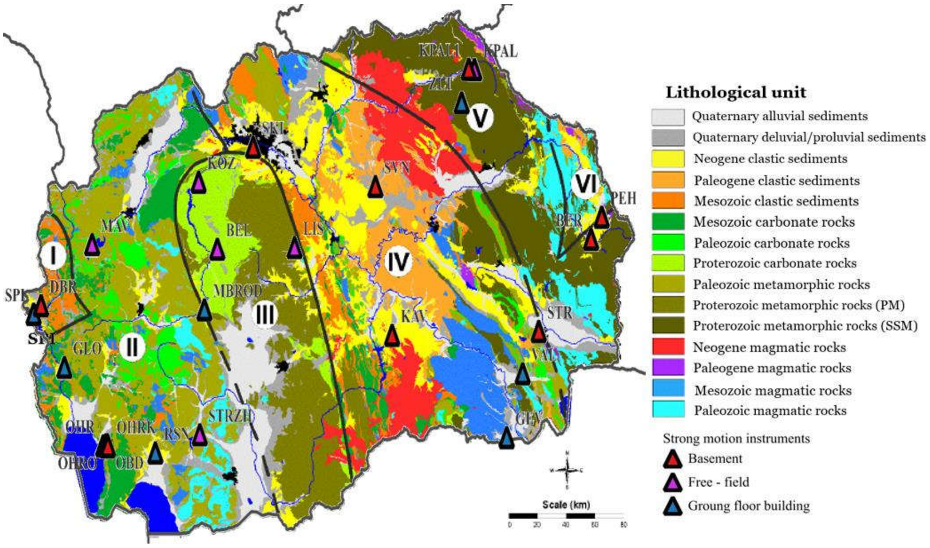

Figure 1. Simplified geological map of the Republic of Macedonia Tectonic units (according to Arsovski, 1997): I – Cukali-Krasta zone (CKZ), II – West-Macedonian zone (WMZ), III – Pelagonian massif (PM). IV – Vardar zone (VZ), V – Serbo-Macedonian massif (SMM), VI – Kraishtide zone (KZ). Updated map from Petrusev et al. 2021 [16] with strong motion instrument's location

Figure 1 illustrates the geological and tectonic units in the study area. The figure is an updated version from Petrusev et al. 2021 [16] and serves as a basis for characterizing strong motion station locations and correlating them with local geological conditions.

The instruments are placed in different tectonic units and geological settings. Installing instruments in various geological conditions, including bedrock and characteristic soil, is crucial for assessing local site effects and understanding how soil properties influence ground motion acceleration.

3. SITE CHARACTERIZATION - DATA

Site characterization is based on data from both active and passive surveys. Active methods include geophysical techniques such as seismic refraction tomography (SRT) and multichannel analysis of surface waves (MASW) [17–22], as well as borehole geotechnical investigations [23]. Passive methods involve single-station H/V spectral ratio analysis using both microtremor and earthquake recordings.

3.1. Geophysical investigations

Geophysical surveys were performed using Seismic Refraction Tomography (SRT) and/or the Multichannel Analysis of Surface Waves (MASW) method at eight existing stations OHR, DBR, PEH, KPAL, LIS, SKI, VAL, OHRK [17-22]. The site parameter V_{S30} is provided in Table 1. Figure 2 illustrates a 3D display of the seismic refraction profiles from the surveys at the PEH station.

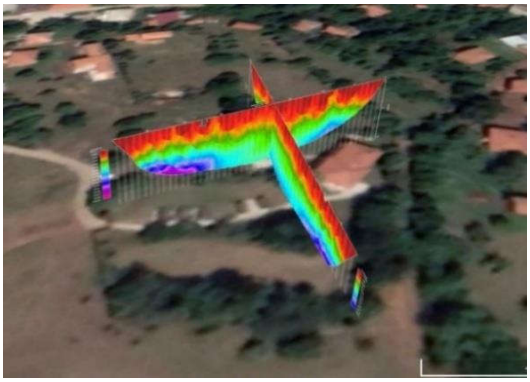

Figure 2. 3D display of the seismic refraction profiles – PEH station

3.2. Borehole geotechnical investigations

The available data from borehole geotechnical investigations date back to the 1980s and were carried out at a maximum depth of up to 120 meters [23]. This data is available only for three stations OBD, OHRK and OHRT. The average shear velocities in the upper 30 m, V_{S30} according to these investigations, are shown in Table 1.

3.3. Site classification based on fundamental frequency

3.3.1. Single station H/V spectral ratio using microtremor measurement data

Single-station H/V microtremor measurements using a TROMINO seismometer were conducted between 2024 and 2025 at twenty-three different locations, in addition to three earlier measurements carried out in 2021. The recording duration for each measurment was 20 minutes, with a sampling frequency of 128 Hz.

Data processing was carried out in accordance with the SESAME H/V User Guidelines [5], using the Grilla software developed by Micromed S.p.A. (2008a). A manual window selection was applied to exclude transient vibrations caused by nearby traffic, incidental movements, or footsteps near the sensors. The average H/V spectral ratios were computed using the Fourier Amplitude Spectrum (FAS) for each component, with smoothing applied following the method of Konno and Omachi (1998) [10]. These results were then used to identify clear H/V spectral peaks, representing the fundamental site frequency and its corresponding amplitude. An example of a microtremor result for STR station is presented in Figure 3.

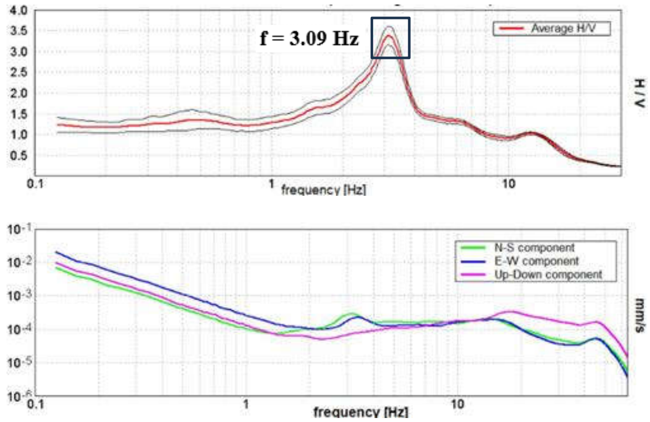

Figure 3. H/V curve and Fourier Amplitude Spectra obtained from microtremor measurements for STR station

3.3.2. Single station H/V spectral ratio using earthquake data

The single-station H/V spectral ratio analysis was performed on recorded earthquake data between 2011 and 2024 within the strong motion network in IZIIS, Skopje. The calculation was based on 5 to 102 earthquake events per station. Before the H/V analysis, the data were visually inspected, baseline corrected, and a bandpass filter ranging from 0.1 to 100 Hz was applied. Bad quality data, and data with SNR < 3 were excluded from the analysis.

The following procedure for H/V was used: different window lengths depending on the earthquake duration were selected, starting before S-wave onset and continuing until the end of the coda wave (Figure 4, a) yellow window). Fourier transformation was used to calculate the Fourier amplitude spectrum (FAS) for each component, two horizontal and one vertical of the earthquake records. Next, smoothing using the Konno and Omachi (1998) [10] window (using bandwidth b=20) was applied. At the end, the average H/V curves were obtained from the horizontal amplitude spectra (using mean value from both horizontal components) and vertical amplitude spectra. The corresponding frequency to the largest amplitude was determined as a dominant, fundamental frequency (Figure 4, b)).

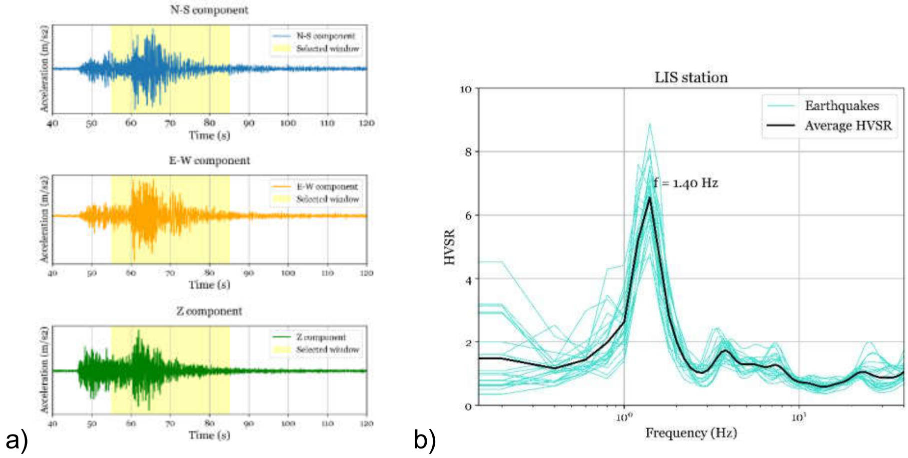

Figure 4. Procedure for H/V calculating using earthquake data, a) strong motion record (earthquake event occurred on 25.04.2022 with magnitude M_w = 4.26, and epicentral distance R_{epi} =111 km) with window chosen (S-wave and coda wave), b) average H/V curve from multiple events

Figure 5 present the obtained H/V curves using microtremors (red color) and earthquakes (black color) for four stations. Four types of results are shown: flat curve with low amplitude values for rock sites (Figure 5, a), clear peak curve (Figure 5, b), multiple peaks curve (Figure 5, c), and high-frequency peak curve (Figure 5, d).

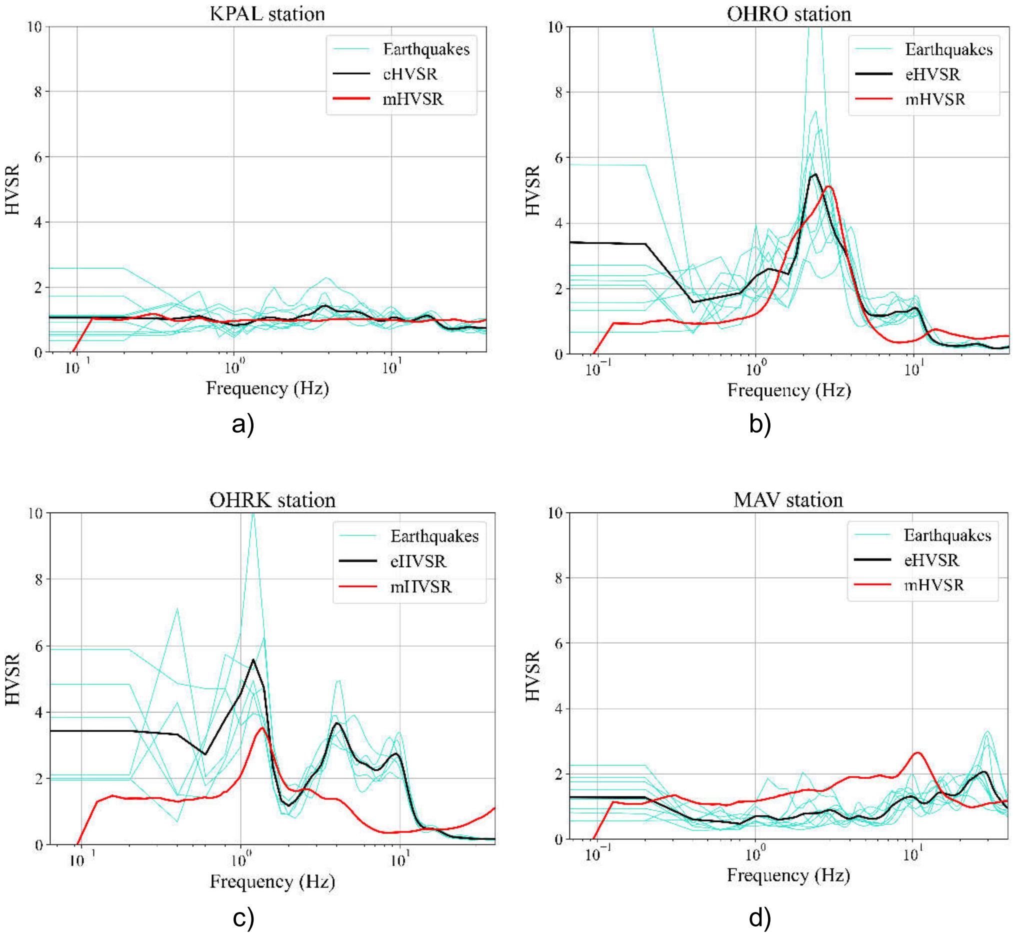

Figure 5. Example of earthquake (eHVSR) and microtremor (mHVSR) H/V spectral ratio – a) flat curve, b) clear high peak, c) multiple peaks, d) high-frequency peak

4. RESULTS

Table 1 presents the station name, V_{S30} values, EC8 site class, fundamental frequencies from H/V analysis (microtremors and earthquakes), number of earthquakes used, and lithological units (with markers matching Figure 1). V_{S30} values retrieved from the USGS V_{S30} Map Viewer [24] are marked with an asterisk (*).

Table 1. Station information, soil characterization type 1^1- geophysics SRT, 1^2- geophysics MASW, type 2 – H/V microtremors, type 3 – H/V earthquakes, type 4 – borehole investigations, N_{eq} number of earthquakes included in the H/V analysis using earthquakes, geological setting corresponding to lithological units in Figure 1. "f" means flat curve, while the symbol "/" indicates no available data. V_{S30} values from USGS are marked with ""*

Station	V_{S30} (m/s)	Site class	Investigation type	f_{0m} (Hz)	f_{0e} (Hz)	N_{eq}	Geological setting
BEL	800*	A	3	/	f	7	
BER	500*	B	2,3	4.2	3.4	25	
DBR	400-450	B	1^1,1^2,3	/	1	102	
GEV	350-380*	B	3	/	f	14	
GLO	800*	A	2,3	11.8	f	5	
KAV	350-380*	B	2,3	F	0.5	9	
KOZ	800*	A	3	/	f	11	
KPAL	>800	A	1^1,1^2,2,3	f	f	9	
KPAL1	350*	C	2,3	4.5	3.5	26	
LIS	350	B	1^1,1^2,2,3	1.5	1.4	23	
MAV	800*	A	2,3	10.7	28.5	9	
MBROD	380-400*	B	3	/	5.8	44	
OBD	350-400	B	2,3,4	1.1	1	36	
OHR	>1000	A	1^1,2,3	f	f	54	
OHRK	350-400	B	1^1,1^2,2,3,4	1.4	1.2	6	
OHRO	350-400	B	2,3	2.9	2.4	9	
OHRT	350-400	B	2,3,4	1.1	1	13	
PEH	380-450	B	1^1,1^2,2,3	f	0.8	47	
RSN	360-400*	B	2,3	0.6	0.6	82	
SKI	330	C	1^1,1^2,2,3	f	f	13	
SPI	800*	A	2,3	21.2	14.4	8	
STR	350-380*	B	2,3	0.9	0.8	28	
STRZH	600-800*	A	2,3	12	10.2	9	
SVN	500*	B	2,3	3.1	1.2	7	
VAL	774	A	1^1,2,3	40	10	24	
ZLT	800*	A	2,3	13.4	f	7	

Figure 6 represents H/V curves obtained from earthquake data recorded at twenty-six different locations. Horizontal black line at H/V=2 represents the non-amplification amplitude following the SESAME criteria [5].

Stations LIS, KPAL1, MBROD, OHRO, and DBR exhibit significant peak amplitudes (H/V > 4) in the frequency range of 1 to 5 Hz, indicating a possible large impedance contrast between the sedimentary cover and the bedrock. It is very likely that ground motion is amplified at these stations.

In contrast, earthquake records from stations GLO, KOZ, BEL, KPAL, and OHR show flat H/V curves, with amplitudes consistently below 2 across the entire frequency range. This indicates insignificant site amplifications, even at higher frequencies.

The SKI station exhibits a flat H/V curve, typically indicative of rock or stiff soil. However, geophysical data reveal unconsolidated sediments extending to depths up to 30m (e.g., V_S < 600 m/s in the upper 12-30 m), explaining the absence of a clear peak. This behavior aligns with the SESAME classification of ~5% of sites showing flat responses despite non-rock conditions.

Stations MAV, SPI, STRZH, and VAL show indications of possible site amplification effects at higher frequencies (20–30 Hz), which may be due to layered weathered rock on the surface. However, the overall site conditions are expected to be predominantly rock.

Stations OHRK, OHRT, OBD, and BER exhibit multiple significant peaks in the H/V spectral ratios derived from earthquake data, while only a single dominant peak is observed from the corresponding microtremor H/V spectral ratio. This difference arises because microtremors mainly consist of surface waves, which do not efficiently exite higher-mode resonances, unlike earthquake-induced motions which contain a broader range of wave types and energy. These peaks, occuring in the frequency range of 1 to 10 Hz, indicate expected site amplification effects caused by the presence of layered, heterogeneous soil structures with varying share-wave velocities. Borehole and geophysical data from the surveys at OHRK, OHRT, and OBD confirm multiple impedance contrasts (e.g., soft surface layers overlying stiffer sediments and bedrock), supporting the interpretation of higher-mode peaks observed in the eHVSR spectra.The observed amplification likely spans a broad frequency range, beginning at the fundamental frequency f_0 and extending to higher modes such as f_1 and f_2.

Stations PEH, STR, KAV, and RSN exhibit an unclear low-frequency peak with small amplitude values (H/V < 4). The absence of a distinct H/V peak may indicate a lack of significant impedance contrast at the site, such as a gradual, normally dispersive profile. According to SESAME [5], this could be due to a moderate impedance contrast depth, a velocity gradient, or low levels of low-frequency ambient vibrations.

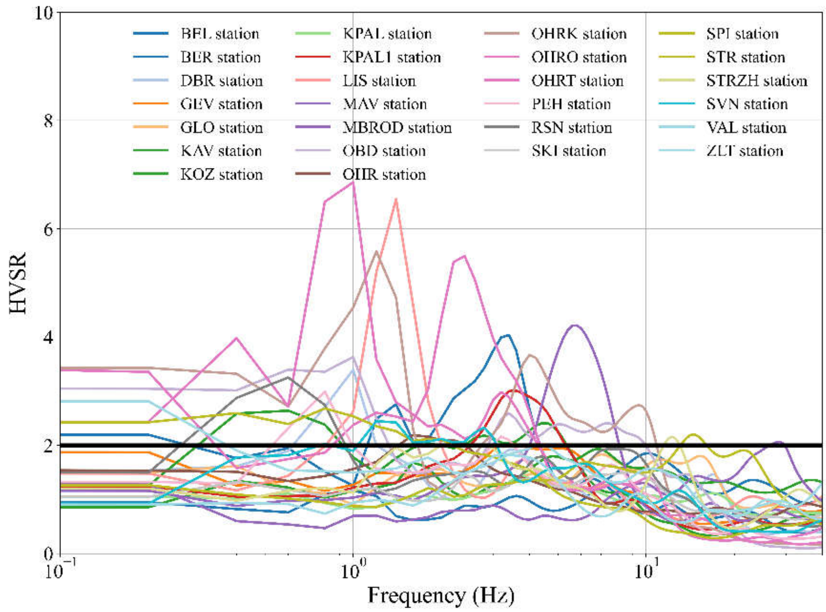

Figure 6. H/V curves for twenty-six stations obtained from earthquakes

The strong motion stations are classified based on their fundamental site frequency determined from earthquake data (marked with different colours), and the soil type according to EC8, V_{S30} parameter (marked with different symbols). The results are illustrated in Figure 7.

The fundamental site frequency (f_0) from H/V spectral analysis is compared with the average shear wave velocity in the upper 30 m (V_{S30}). Figure 8 shows the correlation between

f_0 (from microtremor and earthquake data) and V_{S30}. For stations with a range of V_{S30}, the mean value is plotted. Circles represent measured V_{S30} values, while squares indicate values inferred from the USGS map. The results show that f_0 values from microtremor and earthquake data differ for some stations.

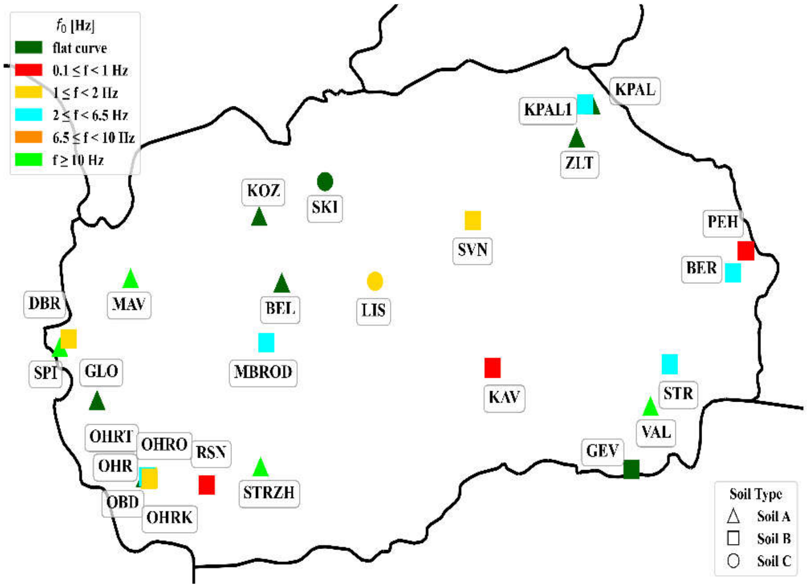

Figure 7. Fundamental frequency map, coloring of the symbols is according to the fundamental frequency value determined from earthquake data using different symbols for soil class according to EC8

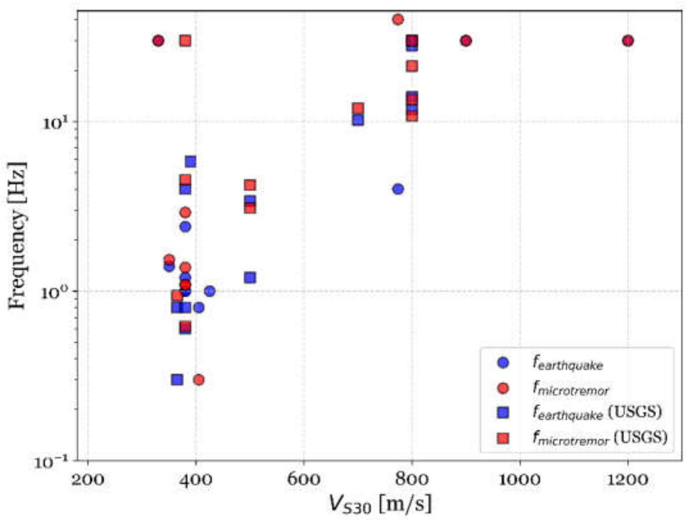

Figure 8. f_0 – V_{S30} distribution obtained from H/V spectral ratio calculations using earthquake data (blue dots) and microtremor measurements (red dots). Circle marker for V_{S30} data obtained from geophysical investigations, and squares from USGS

5. DISCUSSION

This study explored site characterization across strong motion stations in North Macedonia using H/V spectral ratio analysis based on both microtremor and earthquake data. The comparison of fundamental frequencies (f_0) obtained from these two datasets shown differences at several stations. In most cases, microtremor-derived f_0 values were slightly higher than those from earthquake recordings. This difference is likely due to surface waves being more dominant in ambient noise, while the broader frequency range of earthquake recordings allows for the identification of deeper structures and higher-mode resonance.

Figure 8 demonstrates the correlation between f_0 and V_{S30}. Lower V_{S30} values generally correspond to lower f_0 values, as expected for soft-soil sites where fundamental resonance frequencies are lower. However, the relationship is not strictly linear, especially at sites with complex stratigraphy. This suggests that V_{S30} alone may not fully capture the frequency-dependent site response, especially where higher mode resonances are observed (e.g., OHRT, OHRK).

The high-frequency decay parameter κ and its site-specific component k_0 - introduced earlier in the introduction-are key indicators of near-surface attenuation. Their values are sensitive to local damping conditions and are increasingly used in site classification and ground motion modeling. While κ and k_0 calculations are not the focus of this manuscript, the results of this study (particularly the fundamental frequencies f_0 and V_{S30} values) support a more informed selection of boundary frequencies for k estimation and help to contextualize observed k_0 variability in future studies [25]. Previous studies [26-28] have explored the relationship between the site component k_0 and the fundamental site frequency (f_0). In this study, the correlation presented in Figure 8 will be further analyzed to enhance the understanding of site effects and the relationship between k_0 and f_0 for the seizmic stations in North Macedonia.

The results of this study support the ongoing updates to Eurocode 8 (2021 draft) [29], which suggest using f_0 and other spectral indicators along with $V_{S,H}$ based measures. Our findings show that combining f_0 and V_{S30} gives a more complete picture of site response. This approach can help improve national site classification and seismic hazard models.

6. CONCLUSION AND FUTURE APPLICATION

This study presents a site characterization of twenty-six strong motion stations in North Macedonia, using data from previous geophysical and borehole geotechnical investigations, complemented by newly conducted horizontal-to-vertical spectral ratio (H/V) analyses based on both microtremor and earthquake data.

Most stations are classified as EC8 Class A or B, with only two classified as Class C, indicating that the majority of accelerometric stations are located on stiff soils or soft rock. This distribution reflects a general preference for instaling stations on sites with relatively stable ground conditions, which is common practice in seismic monitoring networks.

At locations where multiple investigation methods were available, results show strong consistency, reinforcing the reliability of H/V analysis as a supportive tool in site classification. However, exceptions at stations such as SKI and GEV highlight that relying on a single-method may lead to misleading interpretations of subsurface conditions. These cases emphasize the need for an integrated approach that combines H/V with borehole and/or geophysical methods to ensure accurate site assessment.

The findings of this study are relevant for seismic hazard assessment in the region and contribute to understanding the relationship between high-frequency attenuation (kappa) and site effects characterized by fundamental frequency. Additionally, they support efforts to refine site classification criteria in future updates of Eurocode 8.

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