

EVALUATION AND ANALYSIS OF MICROSEISMIC RECORDS ON THE TERRITORY OF THE SOFIA BASIN

EMIL OYNAKOV¹, RADAN IVANOV^{1*}, LILIYA DIMITROVA¹,
ALEXANDER RADULOV²

¹*National Institute of Geophysics, Geodesy and Geography - Bulgarian
Academy of Sciences, Acad. G. Bonchev St., bl. 3, 1113 Sofia, Bulgaria*

²*Earthquake Geology Department, Geological Institute - Bulgarian Academy
of Sciences, Acad. G. Bonchev St., bl. 24, 1113 Sofia, Bulgaria*

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ABSTRACT: The content of the microseismic wave field continuously recorded at any measurement point is closely related to the structure and geology of the Earth's crust. All registered oscillations have individual amplitude-frequency characteristics, temporal mode of existence and variations (permanent, periodic, spontaneous) and, what is particularly important, characteristic spatial distribution in the geological environment. Seismic noise records were analyzed to study the structure of the microseismic wavefield and the spatial variability of soil dynamic characteristics for the SE part Sofia Basin area. The natural frequencies of the soil were determined by two methods: the standard spectral ratio (SSR) method and the horizontal to vertical spectral ratio (HVSr) method. On the basis of the recorded extensive experimental material, the possibility of using the natural oscillations of the soil (microseisms) for differentiating the ground in a seismic sense has been proven.

KEY WORDS: ambient noise; resonance frequency; ground motion amplification; horizontal to vertical spectral ratio (HVSr).

1 INTRODUCTION

The increased growth of the population and building stock, the concentration of administrative, commercial, industrial and residential buildings, interconnected infrastructure networks (underground and above ground), etc., mean that modern earthquakes can be more damaging to the city than those in the past, even if their magnitudes do not exceed the highest observed so far. The likely secondary effects are also relevant, especially in densely populated areas. The study of microseisms in solving the problems of seismic microzonation is widely used as a detailed and inexpensive

*Corresponding author e-mail: rivanov@geophys.bas.bg

method that provides fairly accurate results. This technique investigates the resonance properties of the upper part of the geological section by measuring microseismic oscillations. The research of Idriss [1], Kramer [2], Reiter [3] and Boncheva [4], shows that during earthquakes, the ground motions recorded on sites with soft soil (e.g., alluvial basins, soft sediments) are significantly larger than those recorded on nearby bedrock. One of the challenges in the practice of earthquake engineering is to evaluate the local ground response to predict the amplification of surface ground motions based on specific geological features of the site, geometries of soil deposits and surface topography, Reiter [3], Meunier [5], Panzera [6]. In practice, the effects of local soil conditions are evaluated using the amplification factor: the ratio of the response of the free surface at the test point and at a nearby point on bedrock, Kramer [2], Reiter [3], Panzera [6]. Unfortunately, in reality the desired seismicity that can satisfy this need is not always available. On the other hand, the use of artificial sources such as high-power explosives and vibrators is impossible and impractical in urban areas. Therefore, ambient noise can be used for this purpose and is a good source for seismic hazard assessment and mitigation in engineering seismology and earthquake engineering studies for urban areas. One of the main tasks of seismic microzonation is to identify zones in the study area with different shaking intensity, due to different engineering-geological, tectonic, hydrogeological, geomorphological and seismological conditions. The horizontal-to-vertical spectral ratio (HVSr) method applied to microtremors, expressed in terms of the natural (fundamental) frequency of the soil and the spectral peak amplitude of the HVSr, introduced by Nogoshi and Igarashi [7] and extensively revised by Nakamura [8], has been used in numerous studies to evaluate the local seismic ground response (Slovenia, Italy, and Croatia), Gosar [9], Di Giacomo [10], Herak [11]. The only application of the HVSr method for the city of Sofia to date is for a single-location measurement performed by Castellaro [12]. The site frequency and peak amplitude calculated by the method provide only an indication of the fundamental frequency and amplification. The site response effects can also be captured by computational methods [13–15], but these require precise knowledge of the geometrical and physical properties of the layers, which are often unavailable. Earthquake and seismic noise records were analyzed to investigate the spatial variability of ground dynamics and to obtain a map of the main ground resonance frequencies for the southeastern part of the Sofia Basin. Soil natural frequencies were determined by two methods: the HVSr (horizontal to vertical spectral ratio) method (Nakamura method) and the SSR (standard spectral ratio) method.

2 GEOLOGIC SETTING

The Sofia sedimentary basin occupies an intramontane depression in the hinterland of the Balkanides [16] that overthrust the Moesian Platform to the north. The Balkanides developed in multiple orogenic phases in between the Adria–Eurasia collision and the Carpathians subduction (Fig. 1a). The final shaping of the orogen was influenced by slab retreat in the Hellenic subduction zone during the Cenozoic times. In the Sofia region, a N–S shortening culminated with thick-skinned thrusting in the Eocene (48–37 Ma) in which process the metamorphic basement was exhumed (Fig. 1b; [17]). The characteristic lithologies in the nappe stacks are volcanic-arc products of a Late Cretaceous age, which belong to the Apuseni–Banat–Timok–Srednogie belt of calcalkaline magmatism [18]. The composition of the nappes, however, is highly variable (Fig. 1b). Sediments of Ordovician to Permian ages prevail in the nappe north the basin, while the southern nappes consist largely of volcanoclastic, volcanic and igneous rocks of a Late Cretaceous age. Clastic and carbonate rocks of Triassic to Jurassic ages crop out in the surrounding mountains, as well as they are involved together with the Late Cretaceous rocks in the underlying bedrock in the basin area. The oblique convergence during the Eocene was accommodated through strain partitioning on strike-slip and reverse faults [19]. These faults played a determining role in the subsequent structural inheritance. Shortening recommenced 30–13.4 Myr ago, when the eastward retreat of the subducted slab beneath the Carpathians and the associated westward indentation of the Moesian Platform in the Carpatho-Balkan orocline (Fig. 1a) resulted in strain partitioning of coeval strike-slip, thrust and normal faults around the indenter [22]. Orogenic collapse had already emerged during this second period of shortening in response to the slab retreat in the Hellenic arc. The edge of the Moesian Platform beneath the orogen extends to the southern Balkan range front, where lithospheric anisotropy likely contributed to strain localization that associates with a series of extensional loci along the range front, expressing a typical basin-and-range morphology. The subvertical bedding plane of Oligocene–earliest Miocene terrestrial deposits near the south of the basin (Fig. 1b) suggests that the strike-slip displacement was significant in the Miocene [23]. The subsequent extensional faults reactivated strike-slip fault portions. Drainage network rearrangement along with the onset of the Vitosha Mountains uplift during the middle to late Miocene (13.8–7.2 Ma) mark the episode Short Title 3 when the extension became dominant in the Sofia region [24]. The sediments of the Sofia basin (Fig. 1b) were deposited in a graben since the late Miocene (Meotian, 7.4–6.1 Ma) [25]. The creation of an accommodation space for a 500–600 m thick deposition occurred together with a raise of the surrounding mountains that exceeds 1500 m above the basin surface. Two basin depocenters, having a local thickness up to 1 km, are located in the

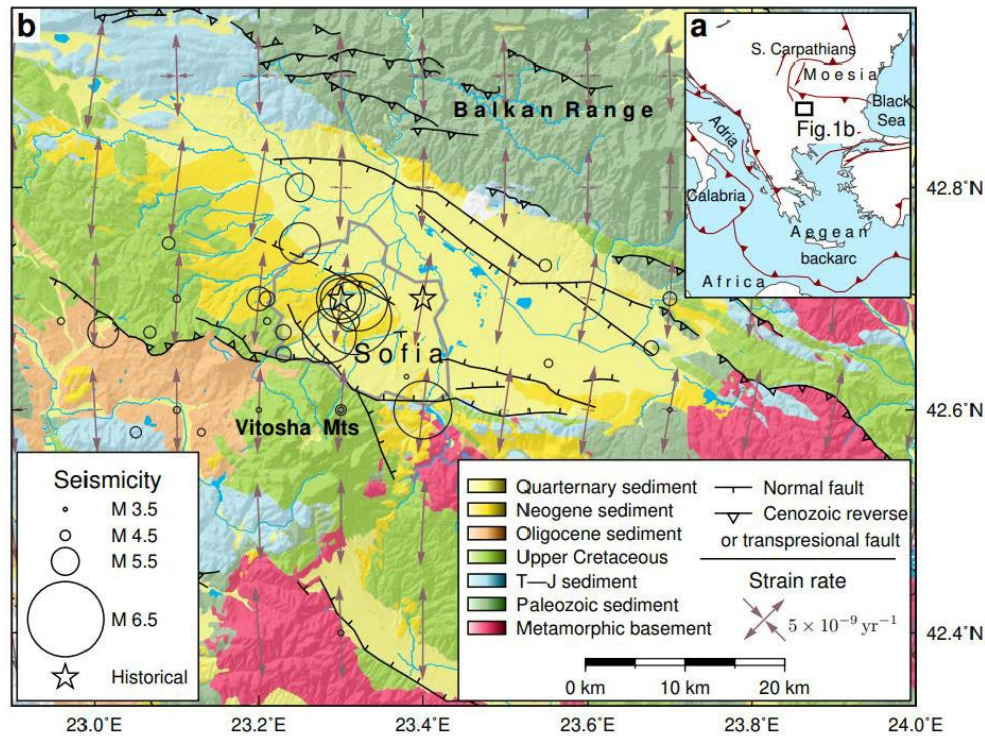


Fig. 1. (a) Regional position of the study area in the Eastern Mediterranean realm. (b) Simplified geologic map, seismicity for the time period 1450–2014 [20] and strain rate from space geodesy (velocity data from Ref. [21]) in the Sofia region.

fault hanging walls. Most of sediments in the Sofia basin were deposited in fluvial and alluvial fan environments. The sediments vary from conglomerate through sand to silt, clay and charcoal. Deposition in lacustrine environment coexisted with an alluvial fan environment during the Pontian (6.1–5.3 Ma). The Neogene and Quaternary layers are separated by a significant erosional hiatus. A factor, which is crucial for the present study, is that the elastic properties of the shallow geologic layer are affected by irregular lateral and vertical changes in sedimentary texture. Distribution of grain sizes is highly variable over small distances. The present-day strain rate field in the Sofia region shows a homogeneity, with an average value of the most extensional eigenvalue of strain tensor in order of $7 \times 10^{-9} \text{ yr}^{-1}$ (Fig. 1b). Faults, which strike mostly obliquely to the extension directions in the ongoing strain rate field, accommodate strain (Fig. 1b). Traces of past earthquake ground ruptures were mapped through field observations on tectonic landforms, fractures, noted in con-

struction excavations, and shallow geophysical surveys [26–29]. The active faults in the Sofia Basin, shown in Fig. 1b, associate with tectonic landforms and are consistent with the faults, which have displaced Neogene layers, based on densely spaced boreholes [25]. The fault along the Vitosha mountain front ruptured the ground surface in the 1858 M_W 6.2 earthquake [30]. Twelve earthquakes from local sources were strongly felt in Sofia since 1450 (Fig. 1b). The 1450, 1749 and 1848 events are provided with little data to assess their magnitudes. Five M_W 6.1–6.5 occurred from 1557 to 1858 [20]. Four M_W 5.5–5.9 were recorded from 1858 to 1895. Background seismicity ($M_W < 5.5$) is frequent, forming a spatial cluster in the Sofia basin. Located in the shallow crust at depths of up to 10–12 km, small size events also cause concern for the local population.

3 METHODOLOGY

Japanese seismologist K. Aki was the first to study the spectrum of seismic noise of the Earth, [31]. If we assume that the stochastic seismic noise wave process is constant in space and time, then the relation between the noise spectral density and the corresponding frequency band of the filtered plane seismic wave can be found. The study of surface waves can be linked to the analysis of the relationship between the horizontal and vertical components of the seismic noise spectrum recorded by a single station. Such an analysis was proposed by the Japanese researchers M. Nogoshi and T. Igarashi in their works: “Propagation characteristics of microtremor”, [32] and “On the amplitude characteristics of microtremor”, [33]. Nakamura reviewed these studies, [8] and suggested that the peaks in terms of spectrum components could be explained by the nature of the profile in the near-surface layer. It is now widely accepted that the peaks are associated in most cases with the surface wave and their analysis gives an estimate of the resonance frequencies of the layered system, [34]. Since its introduction in the last three decades, the HVSr method for non-destructive assessment has been a popular tool for many authors to perform local seismic response studies and perform response and vulnerability analyses; a comprehensive review of the HVSr method is provided in [35]. The method essentially consists of the following steps: split the signal into sequential windows of a particular length, usually 10 s to 60 s, thus removing transients (shocks etc.); for the three components of the signal (NS, EW, V) in the studied window eliminate the linear trend, smooth with a 5% cosine window, construct the spectra applying the Fast Fourier Transform (FFT) in the frequency range 0.1–20 Hz; smooth the window by the Konno-Ohmachi method; compute the H – the RMS of the horizontal components EW and NS; compute the ratio of H and the vertical spectrum; take the average of all windows. The advantages of the HVSr method, in contrast to other geophysical methods (e.g. spectral analysis of surface waves - SASW; multichannel analysis of surface waves -

MASW; seismic refraction - RF and refraction microtremor – ReMI) are its simple, non-invasive measurements and direct evaluation of the seismic effects of the site, e.g. fundamental natural frequency and peak amplitude of the HVSR, and identification of potentially dangerous seismic zones in the studied region at a reasonable cost. Geophysical surveys require profile acquisition over certain distances (often several tens of meters), which is a problem for some sites (historical monuments, slopes, hills, cities, etc.) due to the lack of space, but seismic noise measurements can overcome this. Moreover, Geophysical methods (e.g., MASW) rarely estimate profile depths below 30 m, [36]. The limitations of the microtremor HVSR method are that it does not directly provide 1-D or 2-D soil shear wave velocity (V_S) profiles. V_S profiles and deeper bedrock depths can therefore be estimated by inverting the observed HVSR curve to identify a synthetic HVSR curve that matches a known soil profile, [37, 38].

One of the most popular and widely used techniques when a suitable reference site is available, is the Standard Spectral Ratio (SSR) technique. The SSR is defined as the spectral ratio of the response of a sedimentary site relative to a bedrock reference location, [39]. The records from the reference site (generally a station installed on an outcrop of hard rock) are assumed to contain the same source and propagation effects as the records from the other sites. Therefore, the ratio of the Fourier amplitude spectra expresses only the effect of local soil conditions at the investigated site. For implementing the SSR technique a script was written in the Python programming language, doing the following: choose signals; detrend; taper by 5% Tukey window; compute FFT; smooth the FFT; compute smoothed FFT ratio; weight the ratio by the FFT values of the studied site.

4 DATA AND MEASUREMENTS

The measurements of microseismic noise were carried out in the southeastern part of the Sofia Basin over an area of 290 km², a total of 65 measurements, approximately one measurement in 4 km². All microseismic recordings were made with Etna2 accelerometers with a recording duration of 20 minutes. At most measurement points, the instruments were placed on natural terrain outside of paved areas to achieve good ground contact. The instrument was precisely leveled and oriented: X-axis in the direction of geographic north, Y-axis – to the geographic west. The measurement sites were chosen in the immediate vicinity of boreholes, [40] with a depth of at least 100 m (Fig. 2) so that it is possible to perform a correlation with the borehole data at a later stage.

Most of the microtremor measurements were performed close to the central part of the city of Sofia near to available boreholes, while other measurement locations were chosen to cover typical geological and topographical areas and densify the measure-

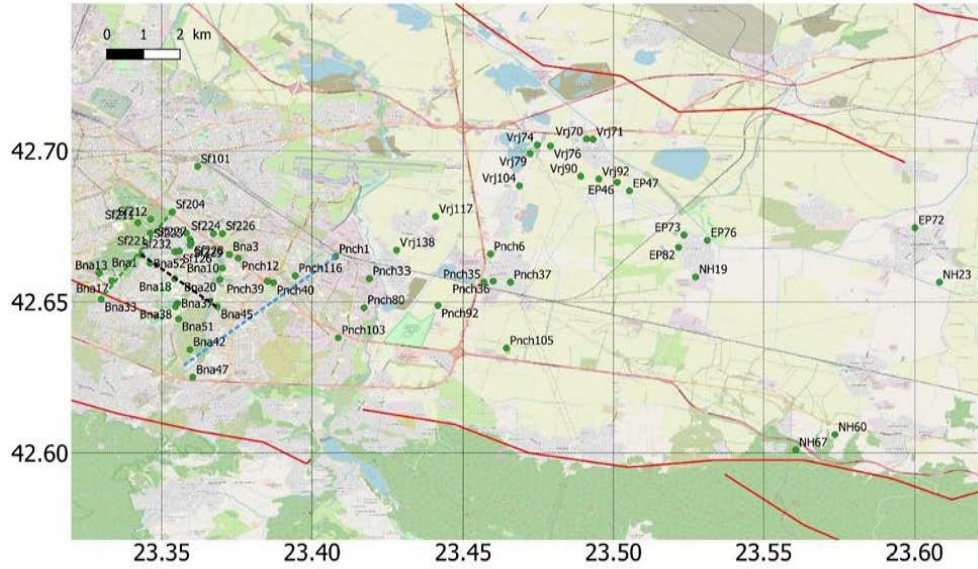


Fig. 2. Studied area and measurement points. (existing faults shown in red).

ment network. The analysis of HVSR microseismic records was performed using the Geopsy software, [41] (<https://www.geopsy.org>) and followed SESAME guidelines for criteria for obtaining reliable measurements and clear peaks, [42].

For the SSR method, velocity data recorded by seismometers of NOTSSI (National Operative Telemetric System for Seismological Information)¹ was taken for four weak earthquakes that occurred during year 2024 on days 64, 74, 121, and 169 of the year with magnitudes between 4 and 5 and epicenters more than 140 km away from the city of Sofia, so that the distance between the reference station Vitosha (VTS) and the studied station SOF (NIGGG) (13.5 km) to be small compared with the distance to the epicenter of each individual earthquake. Also, the epicenters are situated roughly to the North (in Romania), South, East and West (in Serbia), i.e. in all directions relative to Sofia, so that directivity effects could be visible if any.

5 RESULTS AND DISCUSSION

Figure 3 shows an example of the analyzed HVSR curve at a location near bore-hole Bna1 (42.665613 N, 23.343127 E) with an observed peak frequency around 1.0 Hz and an amplitude of 1.34. The difference between a stratigraphic origin and an anthropogenic origin for the H/V peak can be determined by examining single-

¹<https://ndc.niggg.bas.bg/stations/>

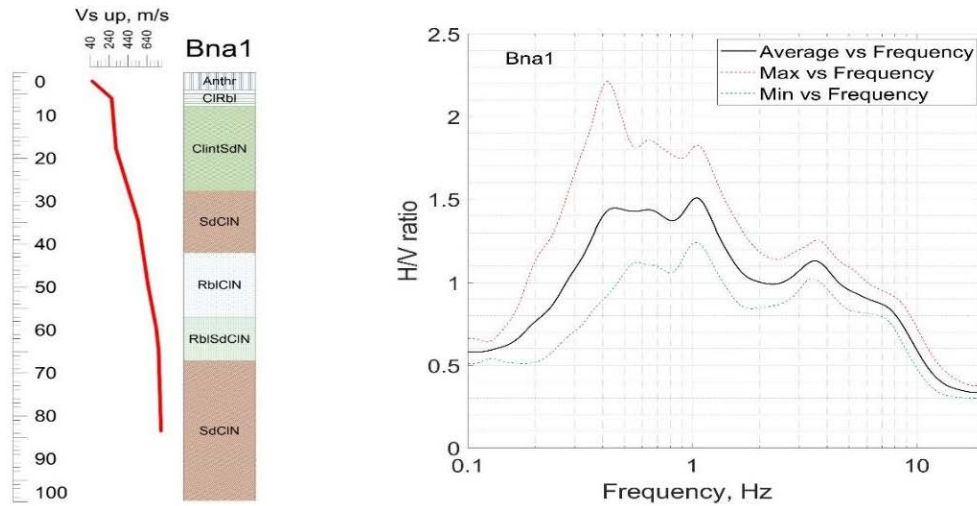


Fig. 3. Data for borehole Bna1 in close proximity to point measurement (left). Example of HVSR curve at the measurement point (right).

component amplitude spectra. The H/V time history plot (Figure 4, left) shows stability of the H/V amplitude during the 20-min recording. Noise windows (transient and stationary near-white noise) are removed from the analysis to obtain the best results. The HVSR polar graph (Figure 4, right) presents the projection of the HVSR in different directions, from 0^0 (N) to 360^0 . Studies by Panzera, [6] and Pischiutta, [43] show that microseismic noise in the fault zones are polarized in a horizontal plane with a trending orientation following the directions of the fault zones near these loca-

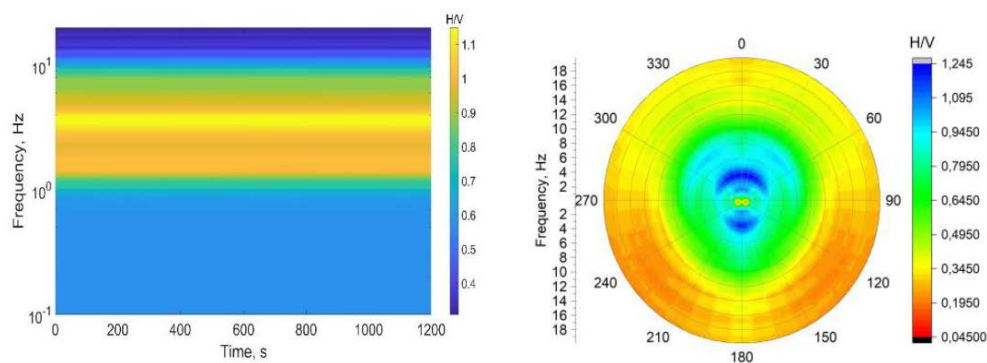


Fig. 4. H/V frequency–time plot (left). Polar plot of the HVSR, the radius plots the frequencies, the color scale represents the amplitudes (right).

tions. In addition, polarization due to the shape and orientation of geologic structures (e.g., topographic ridges) can affect the enhanced ground motion in a particular direction, [5]. Insofar as the amplification of ground motions may result from near-surface impedance contrast due to surface soft deposits (e.g., alluvium) or highly fractured material overlying denser materials, high spectral peak frequencies correspond to shallower sedimentary structures above bedrock, and lower HVSR frequencies indicate deeper soft sediments above bedrock.

Based on the microseismic noise measurements and HVSR analysis, maps of the fundamental soil frequencies and the amplification factor at the peak resonance frequency for the southeastern part of the Sofia Basin were compiled, Fig. 5 and Fig. 6 respectively. The natural neighbor interpolation algorithm was used for the mapping. A direct comparison of the obtained map with the topographic map and geological map of the studied area shows a good correlation between the main soil frequencies and the local characteristics of the studied area (alluvial basin and topographic area). The dominant resonant frequency has a range of 0.2–15 Hz, and the gain at the peak resonant frequency is from 1.04 to 5.57. The lowest frequencies ($f_0 < 1$ Hz) are observed in the soft sedimentary soils throughout the zone, the frequencies slightly increase ($1 < f_0 < 2$ Hz) in the southern part of the area, where is the foot of the Vitosha and Lozenska mountains with characteristic relatively thin and well-compacted sediments over bedrock. Only in four of the measured points located in the southern part of the area the resonance frequency is above 3 Hz (Bna1-3.61 Hz, NH67-4.9 Hz, Pnch103-5.75 Hz and Bna10-15.5 Hz). Figure 6 presents the gain at the peak reso-

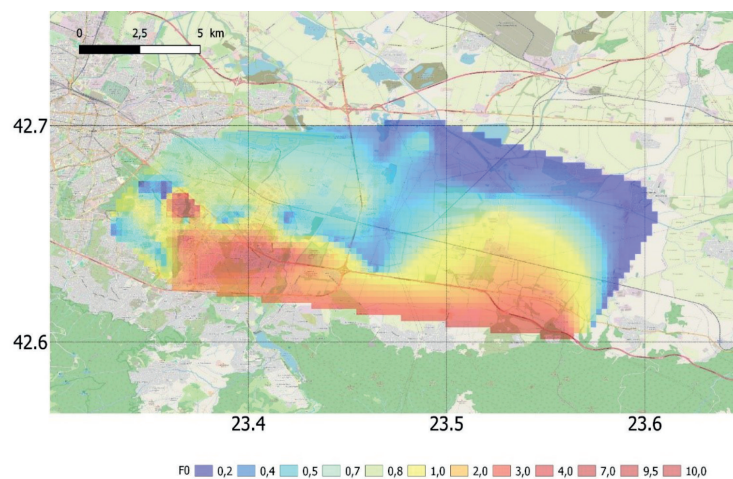


Fig. 5. Distribution of H/V predominant frequency.

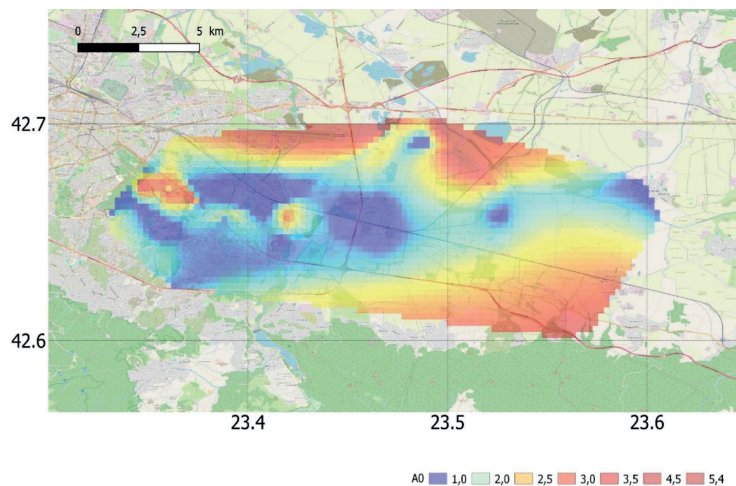


Fig. 6. Distribution of H/V amplitudes.

nance frequency. It is clearly noticeable that a zone with high amplitude (indicated by brighter colors) located in the northern part of the area coincides with the lakes around Dolni Bogrov where sand is mined. Another zone of strong amplification is located in the southeastern part, southwest of Novi Khan (zone Chakarluk) at the foot of the Lozenska mountain (the measuring point is at an altitude of 710 m).

The ratio $K = A_0^2/f_0$ according to Nakamura, [44] is proportional to the dynamic stress caused by seismic vibrations and can be considered as a vulnerability factor. During the 1989 Loma Prieta earthquake in California, a maximum K-index value of

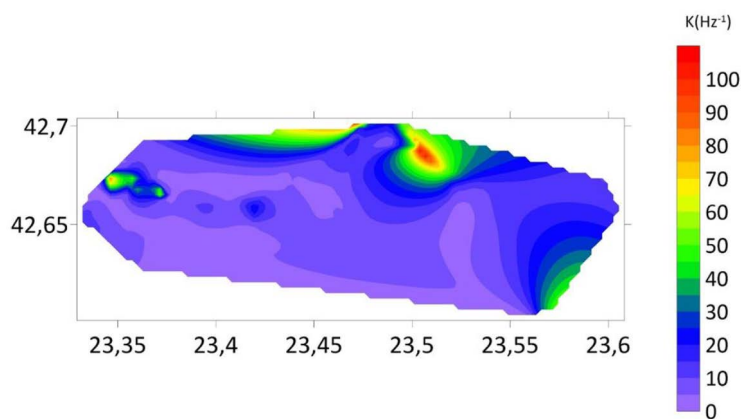


Fig. 7. Distribution of vulnerability coefficient, K.

100 was calculated near the waterfront of San Francisco's Marina District, and most structural damage occurred in areas where the K-value was above 20, [44]. From the obtained gain and peak resonance frequency, it is easy to calculate the K-value of the soil. Figure 7 shows the ground vulnerability in terms of the K-value distribution for the study area obtained by the peak resonance frequency and ground shaking amplification by the HVSR method.

Most of the studied area has a K-value of 10–20. Higher K-values (50–150) are in the northern and southeastern corners of the study area. The ground fundamental frequency map for the southeastern part of the Sofia Basin provides valuable information for the assessment of soil and structure resonance in potential hazardous areas using the relationship between the building fundamental frequency and the height of RC (reinforced concrete) structures, [45, 46].

Extrapolated HVSR amplitude-frequency contours plotted against distance profiles, as shown in Fig. 8, provide the basis for evaluating the resonance characteristics, [47] of selected 2-D profiles. A clear distinction is observed between the change from lower to higher frequencies and higher to lower amplitudes of HVSR in the alluvial basin (profiles P1, P2 and P3, designated with green, black and blue dotted lines in Fig. 2) with respect to the topographic areas. Changes in fundamental resonance frequency are related to the variability of the sediment thicknesses between sites and indicate a relation with the change in site characteristics, e.g. sediment typology, lithology and thickness, soft sediment variations to bedrock depth. Therefore, the HVSR method combined with detailed geotechnical borehole and geophysical surveys is the recommended approach for future engineering geological mapping for the Sofia Basin area.

The results from the SSR spectral ratio analysis for the 74-day earthquake are shown in Fig. 9 as representative of the trends exhibited by the analysis of the rest of the earthquakes too. These trends are as follows: No significant directivity effects, i.e. differences in the ratios for the NS and the EW components are observed in the results, with the peak values of the ratio being between 0.5 Hz and 2 Hz. For some data there are multiple peaks which are clustered over a broad region as in Fig. 9, NS component, which is also true for the 64-day earthquake and 169-day earthquake (both components), and the 121-day earthquake (EW component). For some of the data well-defined single peaks are observed as the in Fig. 9, EW component, which is also true for the 121-day earthquake (NS component). The EW components of the 121-day earthquake and the 169-day earthquake could also be put in this category, although strictly speaking they have two peaks. If we compare the SSR results to the H/V results shown in Fig. 10 the following observations and interpretations can be made: if we look at the basement data, there is a significant difference in the peaks, with the H/V peaks being below 1 Hz and the SSR peak above 1 Hz. A

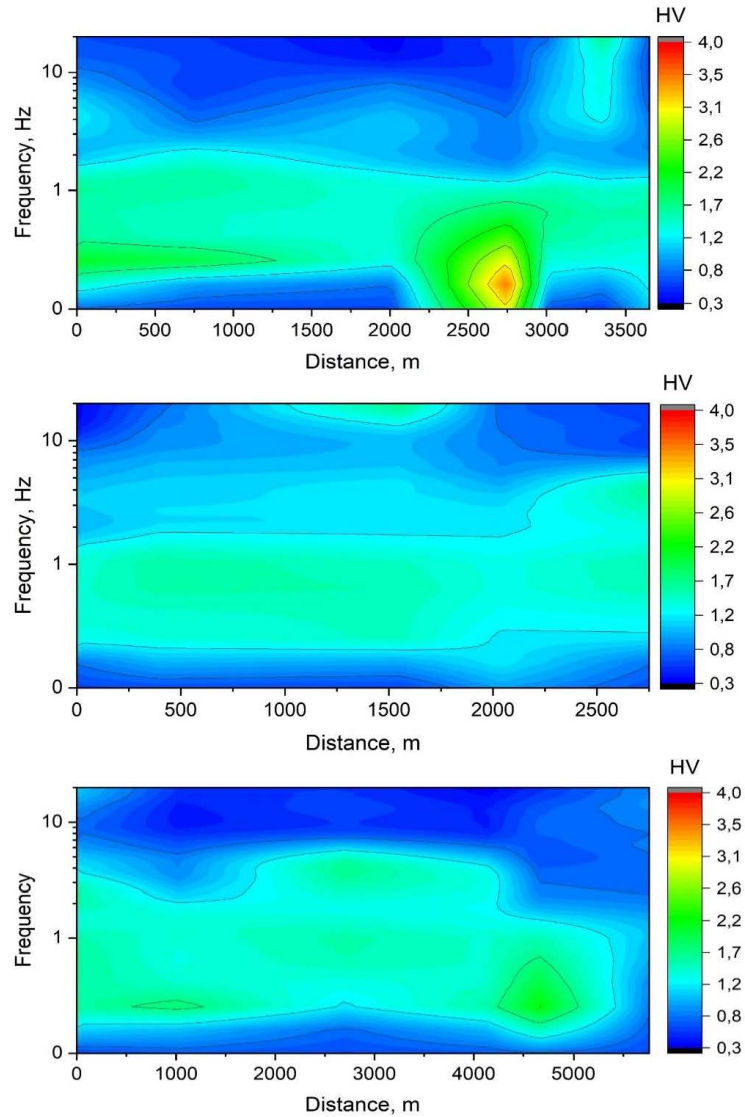


Fig. 8. Frequency-amplitude profiles: P1(top), P2(middle), P3(bottom).

rational explanation for this can be the fact that the data of the much stronger signals (real earthquakes) used in the SSR analysis contain the building response, which is in the range above 1 Hz, while the ambient vibrations are not enough to trigger a strong response of the building. Therefore, no building response is transmitted to the basement unit, which is installed on a foundation isolated from the building foundations.

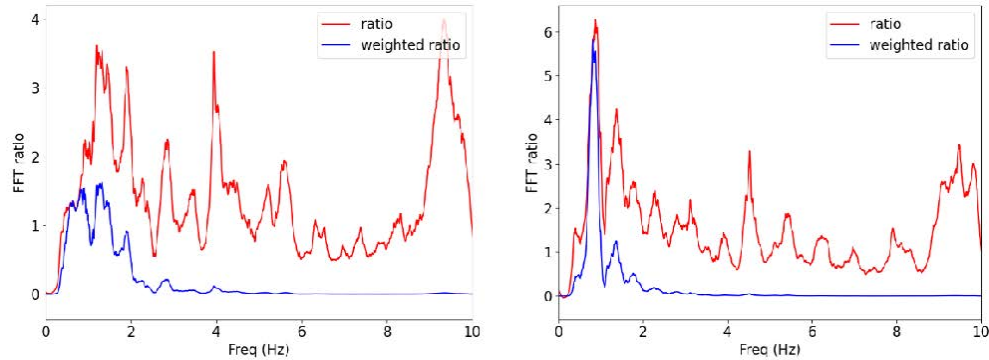


Fig. 9. SSR for 74-day earthquake: NS component(left), EW component (right).

On the other hand, the H/V ratio obtained for data in the vicinity of the building has an obvious peak around 1 Hz which is in good agreement with the results from the SSR analysis, meaning that it is also contaminated with the building response. Considering all of the above, we can conclude that neither the SSR results nor the H/V results are indicative of the true free-field dynamic characteristics of the soil for this particular site, due to the installation location of the seismometer used in the SSR study.

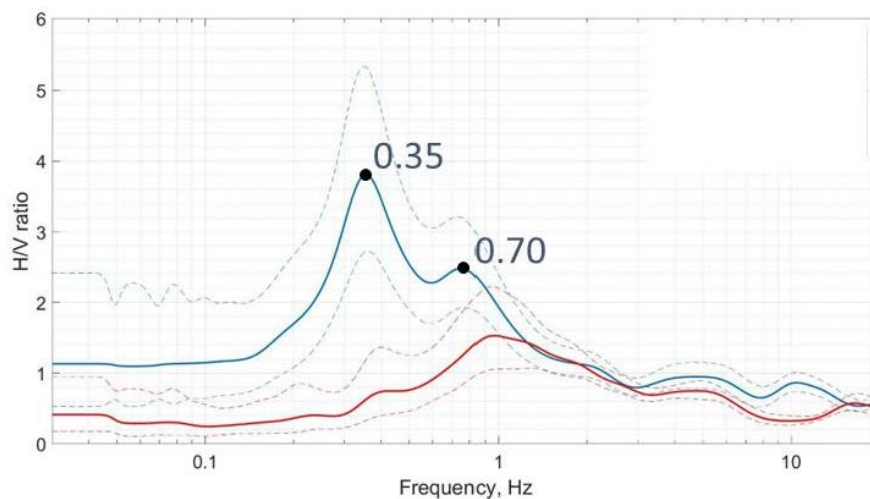


Fig. 10. H/V spectral ratio: basement (blue), vicinity of building (red), NIGGG site.

6 CONCLUSIONS

The H/V spectral ratio method was used for a seismic microzonation study of a vast region in the South-East of the city of Sofia. The predominant frequencies of the soil at 65 locations within the region were directly obtained from the measurements, and used to construct a map of the predominant frequencies for the whole region.

A companion study was done by the SSR method, which for the city of Sofia is currently possible for one location only. This study made it clear that an array of permanent free-field measurement stations would be needed to implement a large scale SSR study. On the other hand, with the H/V method, there is a relative freedom in choosing the measurement locations, and there is no need for setting permanent stations, which makes the HVSR method much more flexible and accessible than the SSR method, at least for the case of the city of Sofia.

The obtained predominant frequencies can be used as guidance for choosing appropriate ground motions for the seismic analysis and design of buildings and facilities to be constructed in the studied region. Drawing on the gained experience, the study will be extended to cover the whole of the Sofia metropolitan area, thus contributing towards optimal seismic design for the whole city.

6.1 ACKNOWLEDGMENTS

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