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GEOPHYSICAL RECONSTRUCTION OF BEDROCK DEPTH AT THE LARGE SINKHOLE IN THE 2020 PETRINJA EARTHQUAKE

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Abstract

This paper shows the results of bedrock depth analysis around the largest cover-collapse sinkhole that occurred during the 2020-2021 Petrinja earthquake sequence. Horizontal to Vertical Spectral Ratio (HVSR) data was collected by the Geotechnical Extreme Events Reconnaissance (GEER) team after the Mw 6.4 December 2020 Petrinja earthquake in Croatia. In addition, the GEER team collected other data to assess the damage and geologic conditions, including two geotechnical boreholes with field and laboratory data and Multichannel Analysis of Surface Waves (MASW) profiles. Out of 61 HVSR readings performed during reconnaissance, 15 are around the largest sinkhole, S001, about 25 m wide and 12 m deep, with vertical walls and groundwater. The soil in the area consists of a clayey cover that is 4.0 m to 10.0 m thick, with sporadic gravel lenses. Clays are mostly over-consolidated, with varying degrees of saturation with intensely karstified carbonate rocks underneath. The HVSR data was analyzed using the HVSRweb platform and associated Python-based modules incorporating various statistical assessment models include single azimuth, multiple-azimuth, and geometric mean. The geometric mean results based on resampling frequencies between 3 Hz and 10 Hz indicate karst depths between 12.0 m and 18.0 m, which is generally consistent with the bedrock assumed from the sinkhole depth. Furthermore, an evaluation of the spatial variability of the resonance frequencies and the corresponding depth estimates assesses the presence and orientation of karstic features around S001. Based on the assessed data, HVSR measurements appear to be a helpful tool for evaluating variations in subsurface impedance contrasts and can be used to augment geotechnical data and other geophysical measurement techniques due to the relative ease of deployment and rapid data acquisition.

Keywords: Horizontal to Vertical Spectral Ratio (HVSR), sinkhole, post-seismic effect, karst geophysics

1. Introduction

On December 29, 2000, an earthquake with a moment magnitude of M_W 6.4 occurred in the Sisak–Moslavina county in Central Croatia at 12:19 PM local time (11:19 AM UTC; USGS 2020). According to the US Geological Survey, the earthquake hypocenter was at 45.422°N 16.255°E, at a depth of 10 km [1] within the central portion of the shallow Petrinja strike-slip fault in the marginal part of the Internal Dinarides, NE part of the Adria Microplate. Three foreshocks preceded the earthquake for one day, the strongest of which had a magnitude of M_W 5.2, followed by numerous aftershocks. In the first 60 days of the sequence, 4430 events were located within 50 km from the mainshock, including 85 aftershocks with a local magnitude $M_L \geq 3.1$ until February 22, 2021. Most aftershocks in the central cluster are distributed between 13 km and 17 km depth. Maximum depths below 25 km are observed only in the central cluster part, while the first 5 km of the crust hosted a small number of events through the entire cluster. Within the central cluster, the event distribution delineates a sub-vertical fault containing the mainshock. As a result, the earthquake caused widespread damage in Petrinja, Sisak, Glina, and the surrounding villages, and seven people lost their lives. According to the Croatian Seismological Survey data, the epicentral intensity was estimated to be VIII–IX EMS [1].

This paper focuses on analysing some aspects and features of a relatively rare post-seismic effect, a sinkhole collapse near Mečenčani and Borojevići villages 20 km SE of the mainshock epicentral area. Geotechnical Extreme Events Reconnaissance (GEER) team obtained data that support this study. GEER registered 91 new cover collapse sinkholes and 45 historical cover collapse sinkholes, opened

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before the Petrinja earthquake [1]. All new sinkholes are within two small areas, 1.13 km^2 combined: 74 in the NW area close to the Borojevići village over approximately 0.753 km^2 and 48 in the SE area around Mečenčani village over approximately 0.375 km^2.

The uniqueness of the sinkhole region is that this is the only region where karstic geologic conditions were close to the epicenter. Highly karstified limestones are directly covered by relatively thick clayey soil. Middle Miocene carbonates (Badenian, M4) are composed of alternating highly porous Lithothamnion limestones and calcarenites, both very susceptible to karstification, as visible in the hills SW of the studied area [2, 3]. Karstified carbonates are overlain by a 4–15 m thick sequence of Holocene diluvial–proluvial deposits. Deposits are unsaturated to saturated clays with lenses of gravel and sand. Hydrological investigation reveals two distinct aquifers that are interconnected sporadically. The Sunja river valley in the studied area represents a flat terrain covered with Holocene diluvial–pluvial deposits of low permeability containing a certain amount of water and therefore forming an aquitard with the groundwater level fluctuations between dry and wet periods of about 2.0 m. The aquitard is underlain by a permeable confined karst aquifer, in which the water pressure during wet periods becomes sub-artesian to artesian [1].

This paper uses a combination of geophysical methods and horizontal to vertical spectral ratio (HVSR) to better understand the spatial horizon variations between clayey cover and underlying karstic rock around the largest sinkhole, S001. The geophysical investigation is supported by geotechnical soil investigation works and imaging [1]. The S001 sinkhole is the largest sinkhole that occurred in the area until the GEER field trip in middle March 2021. Fig. 1 shows the sinkhole lidar images and position. Fig. 2 shows geotechnical boreholes around the S001 sinkhole. Unsatureated and saturated low to high plasticity clays overlay karst. The extensive report of geotechnical research and investigation is presented in Tomac et al., 2022 [4]. Initial measurements of groundwater levels during drilling are shown in Fig. 2 and are between 4.0 m and 4.6 m depth. After a few hours, the groundwater level in boreholes were measured again and corresponded to the water level in the sinkhole [4].

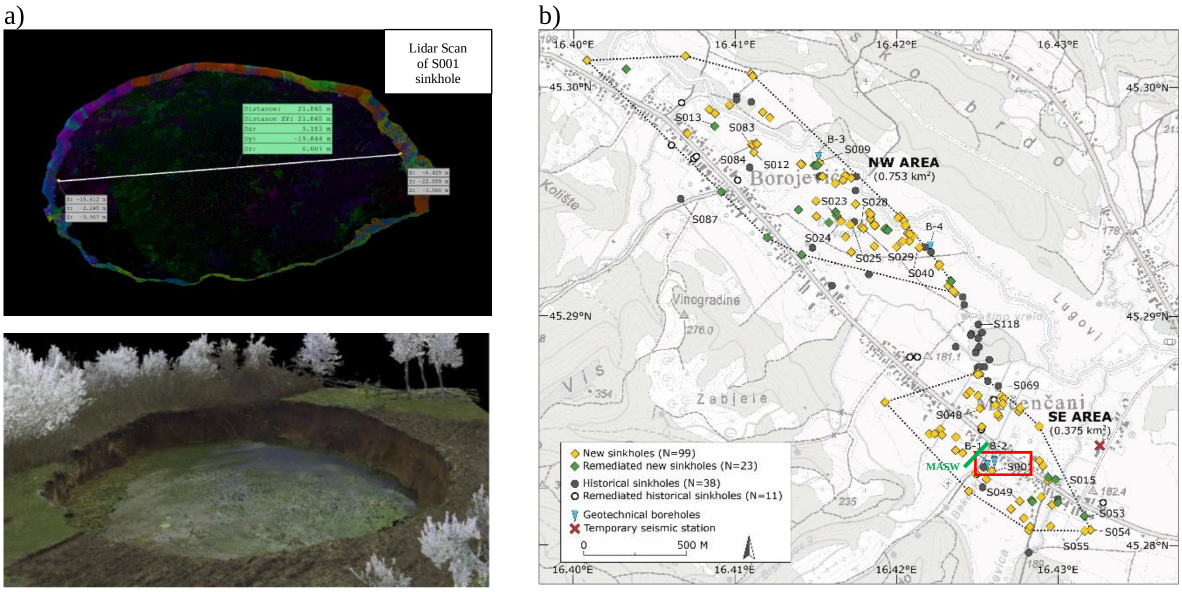

Figure 1. a) S001 (45.2833444N, 16.4259639E) imagery (modified from [1]); b) Sinkholes position on the map (modified from [3]).

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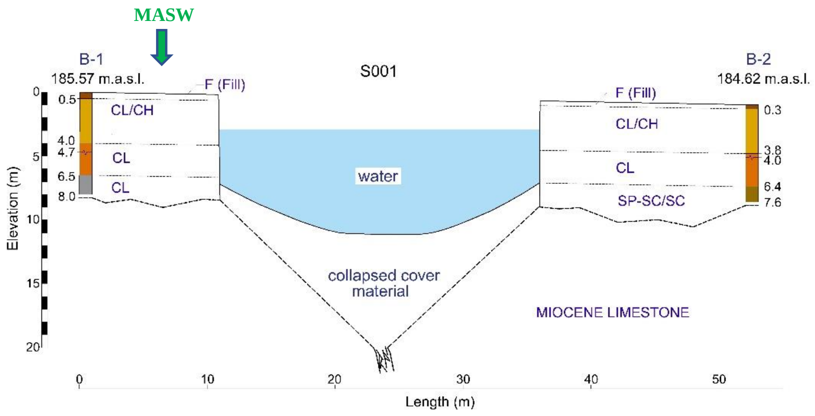

Figure 2. Sinkhole S001 (45.2833444N, 16.4259639E) geotechnical profile and MASW location (modified from [4]). Borehole depth is dependent on manual drilling equipment capabilities, where the bottom indicates the upper horizon of the weathered karst layer.

2. Methodology

HVSR in ambient noise measurements is commonly used to estimate site resonant frequency providing excellent estimates of resonant frequency for sites with strong impedance contrasts. Following the 2020 Petrinja Earthquake in Croatia, the GEER reconnaissance team [1] performed nanometrics measurements at 61 locations during their assessment to gain an understanding of the site resonant frequencies which are important in understanding seismic wave propagation. In addition, it was anticipated that the HVSR measurements could provide an additional tool for assessing depth to bedrock as well as for investigating karst features which are common in the sinkhole reconnaissance area in Mečenčani and Borojevići.

In this paper, an evaluation of the nanometrics data is performed to augment the results presented in the GEER report to incorporate sensitivity analyses to various factors including sampling frequency range and spatial and azimuthal variability. The presented analyses limits to the nanometrics measurements around the largest sinkhole S001. S001 developed a few days after the earthquake and was estimated to be about 25.0 m wide and 12.0 m deep by the GEER team end of March 2021. The impedance contrast depths are calculated from the following formula based on the estimated site resonant frequency for each azimuth [5]:

$$D = \frac{V_s}{4 \times f_o} \quad (1)$$

Analysis of the nanometrics data is performed using the web platform HVSRweb as well as associated Python-based modules that are part of the hvsrpy package, previously validated by Vantassel et al. [5], Vantassel [6], Cox et al. [7] and Cheng et al. [6]. Analyses are performed using the various statistical assessment models in hvsrpy including single azimuth, multiple-azimuth and geometric mean. Sensitivity analysis on azimuthal variability of the site resonant frequencies investigates a scatter in frequencies across azimuths from 0° to 180°, including the variability of the site resonant frequencies and the standard deviation at each azimuth. Additionally, the sampling frequency range is varied to assess whether the results would indicate the presence of strong impedance contrasts at shallower depths, consistent with potential depths of karst features. An evaluation of the spatial variability of the resonant frequencies around S001, and the corresponding depth estimates, also provide insight into potential presence and orientation of karst features around S001.

2.1 Initial Assessment

An initial assessment of the nanometrics data is performed for positions N-38, 44 through 48, 50 through 53, 55 through 59, and N-61 to evaluate overall HVSR frequencies and information on depths of strong impedance contrasts. The analysis is performed for data from nanometrics measurements around the area of S001, the measurement locations are show in Fig. 3.

Figure 3. Sinkhole S001 and nanometrics measurement locations (modified from [1])

The initial assessment evaluates the HVSR across the full range of ambient noise frequencies between about 0.1 Hz and 50.0 Hz. An example summary of the HVSR data is presented in Figure 4. The HVSR assessment is performed using HVSRweb and the following settings is shown in Table 1. The data indicates high random peaks at frequencies below 0.3 Hz that appeared to be transient noise and the lower resampling frequency is therefore adjusted to 0.3 Hz. The geometric mean results based on resampling frequencies between 3.0 Hz and 10.0 Hz indicate potential bedrock depths between 12.0 m and 18.0 m around S001, which is generally consistent with the bedrock depth assumed from the sinkhole depth [2]. For example, the data appear to be of good quality with some distinct peaks interpreted to correspond to shallow (2.0 m to 5.0 m) and deep (20.0 m to 40.0 m) impedance contracts below ground surface. However, soil borings, as shown in Fig. 1, that were performed adjacent to the sinkhole S001 during the GEER team's site assessment meet refusal at depths between 7.6 m and 8.0 m [2, 4]. The refusal depths were interpreted as corresponding to bedrock depth although no bedrock samples could be obtained due to drilling equipment limitations. Fig. 5 shows a Multi-Channel Analysis of Surface Waves (MASW) survey performed along the eastern side of S001 indicated that there could be strong impedance contrasts at depths between 8.0 m (transition from v_s ~ 200 m/s to 300 m/s) and 12.0 m (transition from v_s ~ 400 m/s to 500 m/s) [2]. The transition to shear wave velocity of >500 m/s at 25.0 m depth corresponds to very stiff soil or soft rock conditions based on typical seismic site classification criteria. Since the initial assessment did not indicate strong impedance contrasts within the anticipated bedrock depth (8.0 m to 16.0 m) obtained from MASW and geotechnical boreholes, a narrower resampling frequency range is selected for the next round of assessments.

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Table 1 HVSR Initial Data Processing Inputs

Window Length (sec)	60 and 120
Cosine Taper Width	0.1
Butterworth Filter	No
K-O Smoothing Coefficient	40
Resampling Frequency Min (Hz)	0.3
Resampling Frequency Max	50
Number of Frequency Points	200
Type	Logarithmic
Distribution of f_0	Lognormal
Frequency Domain Window Rejection	Yes

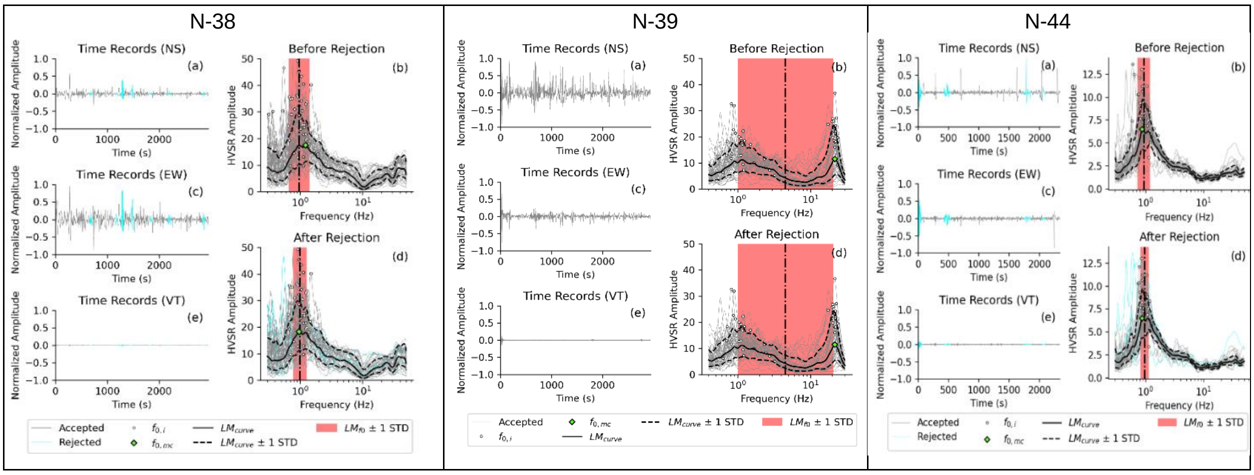

Figure 4. Example nanometrics results from initial assessment.

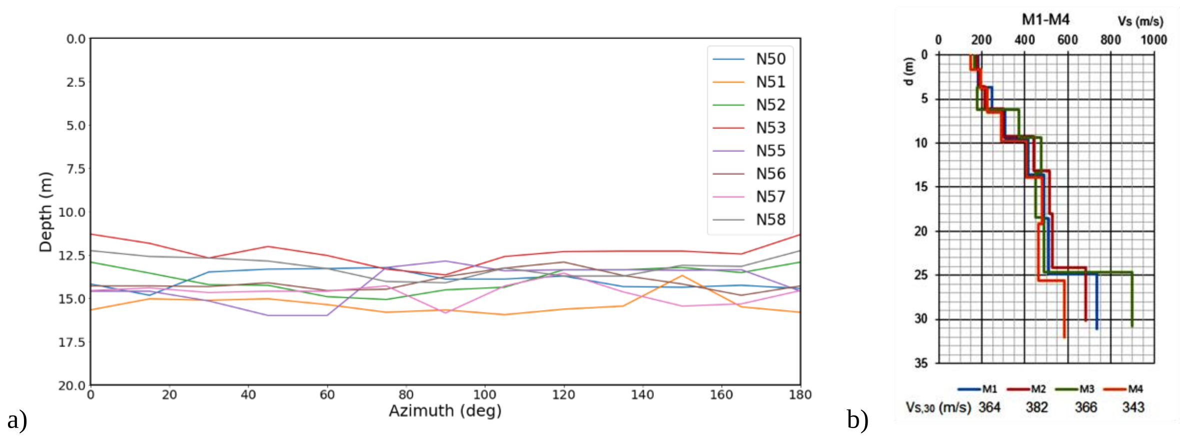

Figure 5. Weathered karst depth estimates s) azimuthal variability from the sinkhole S001 median frequencies and b) MASW profile across S001 (45.2833444N, 16.4259639E) from GEER reconnaissance [1].

2.2. Resampling Frequency Variation

Since the initial assessment did not indicate strong impedance contrasts within the range of interest and suspected karst horizon, another round of data assessments is performed with a narrower resampling frequency range. The analysis settings were the same as those presented in Table 1 except that the

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frequency ranges considered were 3.0 Hz to 10.0 Hz and 3.0 Hz to 50.0 Hz. The goal is to assess whether the data would indicate strong impedance contrasts at depths between about 6.0 m and 18.0 m to cover the range of anticipated bedrock depth below ground surface. This round of sensitivity checks is limited to sites N-55 and N-56 adjacent to sinkhole S001 to gain an indication of the impact on the overall results before applying similar frequency ranges to a wider range of nanometrics data. The results of the resampling frequency variation are summarized in Table 2, Fig. 6.

Table 2 N-55 and N-56 HVSR Re-sampling Frequency Variation Data Summary

Site	Min	Max	Component	$f_{o,mc}$ (Hz)	Apparent Bedrock Depth (m)
N-55	0.3	50	Geomean	1.5	36.7
	3	50	Geomean	27.4	2.0
	3	10	Geomean	4.63	11.9
N-56	0.3	50	Geomean	1.62	34.0
	3	50	Geomean	33.5	1.6
	3	10	Geomean	4.55	11.1

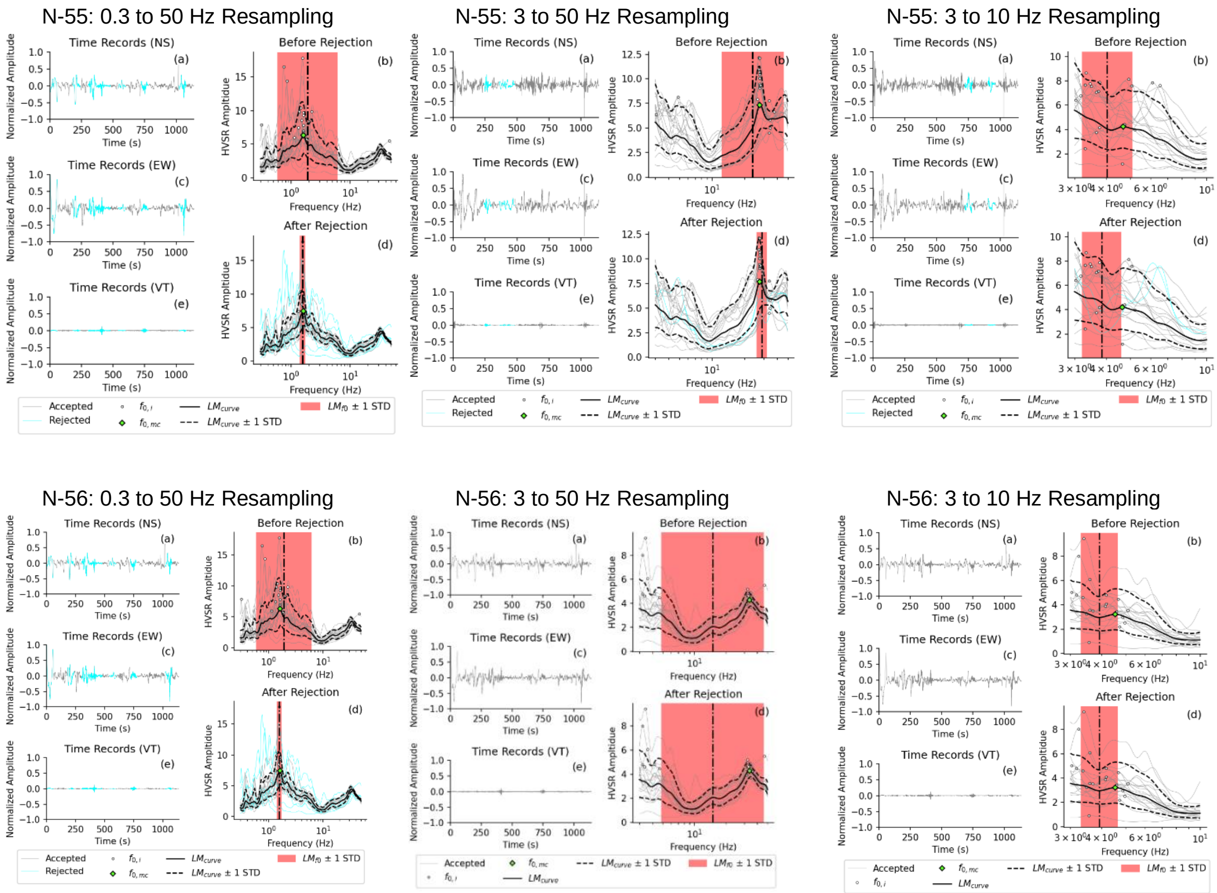

Figure 6. N-55 and N-56 HVSR re-sampling frequency variation summary plots.

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2.3. Azimuthal Variation

Estimates of site resonant frequency from HVSR are subject to various sources of uncertainty due to the random nature of ambient noise in space and time, variations in subsurface conditions and sensor coupling conditions. To assess a potential impact of spatial variations on the site resonant frequencies from the nanometrics around S001 (N-50 through N-58), additional sensitivity analyses are performed on azimuthal variability of the results (N-54 data was not included due to data quality issues). The sensitivity analysis of azimuthal variability of the site resonant frequencies at 15° intervals indicates a scatter in frequencies across azimuths from 0° to 180° for most of the measurement locations. The variability is noted in both the site resonant frequencies as well as the standard deviation at each azimuth. The observed scatter may be due to lateral variability as azimuthal variability can be expected for subsurface conditions with significant lateral variability [5].

The results are also compared to the geometric mean results of resonant frequency across all azimuths. The assessment of azimuthal variability considered both the median resonant frequency and the peak frequency of the median curve. The impedance contrast depths corresponding to either the median or peak frequency appeared to be consistent with the MASW data collected by the GEER team at S001. Overall, the peak frequency values provide a better average fit to the MASW data. It should be noted that estimates of the impedance contrast depths were obtained from the quarter wavelength solution based on an average shear wave velocity of 220 m/s considered for the near surface deposits by the GEER team [1].

2.4. Spatial Variability

The next stage in the analyses is to assess variations in estimated depths of the strong impedance contrasts (apparent bedrock depth) across the measured locations. The assessment is performed for the nanometrics locations around S001 and locations N-44 through N-48, located in vicinity of S001.

The assessment of spatial variability is performed using the spatial interface Python module of hvsrpy. The algorithm uses Voronoi tessellations to obtain a statistical representation of site resonant frequency (or period) from spatially distributed HVSR measurements [6]. The assessment requires setting area boundaries and providing coordinates, the mean or peak resonant frequency and the natural log of the standard deviation of the site resonant frequency at each coordinate. The algorithm then applies Voronoi tessellation to yield unique spatial estimates of site resonant frequency.

The results of the spatial variability assessment are summarized in Fig. 7 showing site resonant frequency and bedrock depth estimates results for all the assessed locations and Fig. 8 showing data for locations around S001. The data appear to indicate several steep changes in bedrock depth in several directions around the sinkhole area which may indicate the presence of karst voids or potential fluid flow channels. The steep changes appear to be oriented in the southwest-northeast direction.

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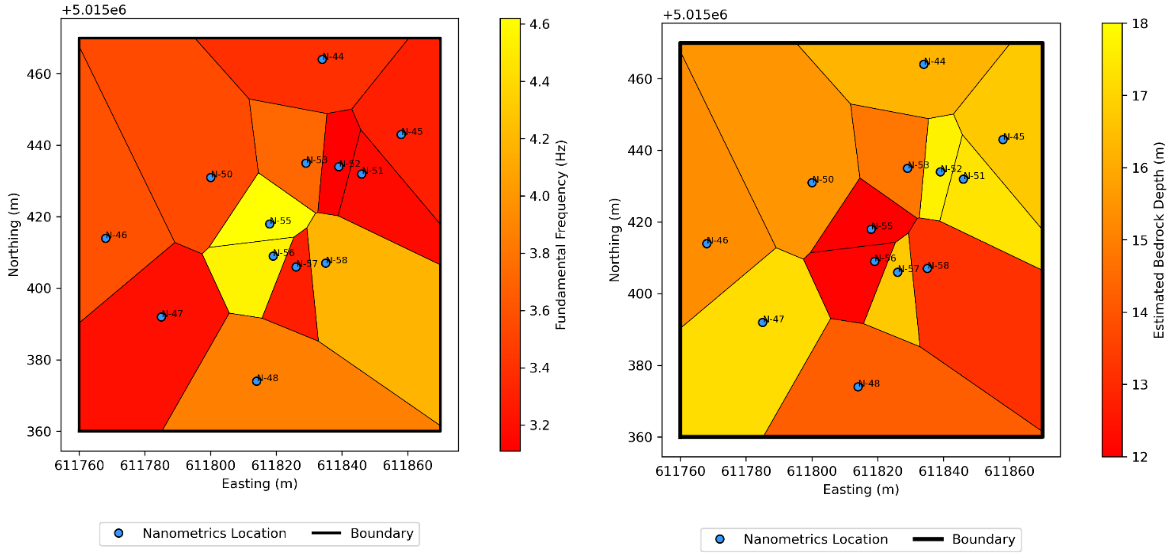

Figure 7. Spatial variation of site resonant frequency and bedrock depth estimates (N-44 to N-58).

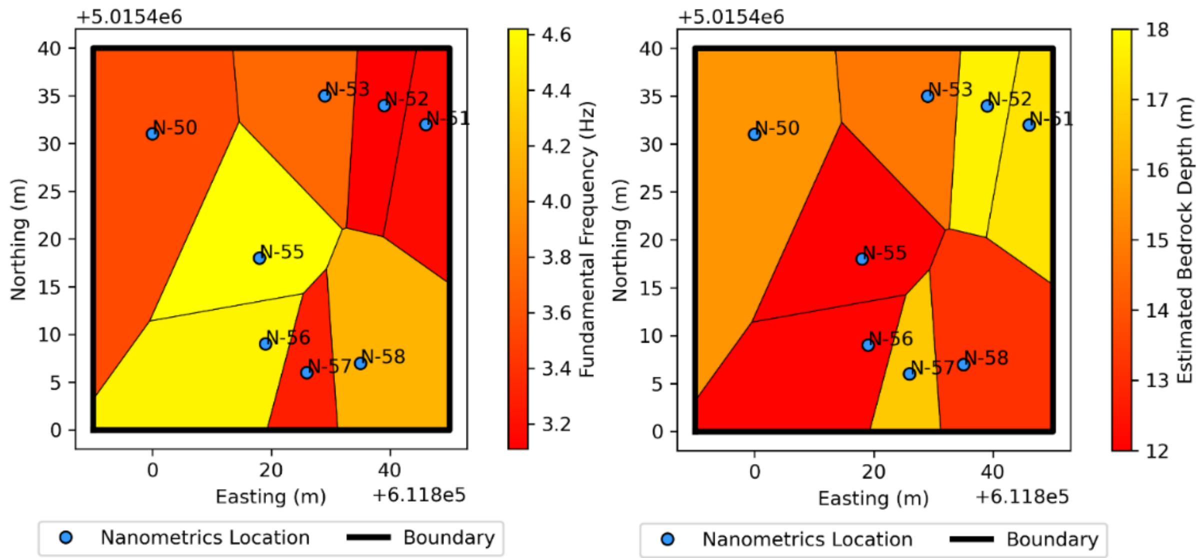

Figure 8. Spatial variation of site resonant frequency and bedrock depth estimates (around S001).

To better visualize the apparent steep changes in bedrock depth around the sinkhole, a three-dimensional plot of the data is developed as presented in Fig. 9 and Fig. 10. In Fig. 9, the cylinder represents sinkhole S001 only schematically, where the diameter corresponds to the reported diameter measured at the soil surface, and the in-situ sinkhole walls are vertical. The shape of the sinkhole under water has not been measured accurately, beyond detecting the collapsed material at the bottom, as shown in Fig. 2.

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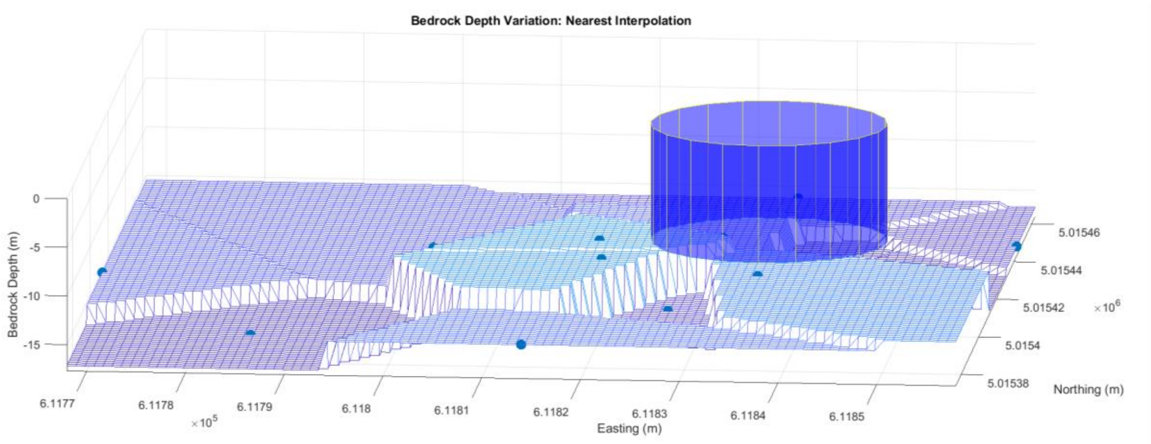

Figure 9. Bedrock depth estimates around sinkhole S001, looking north.

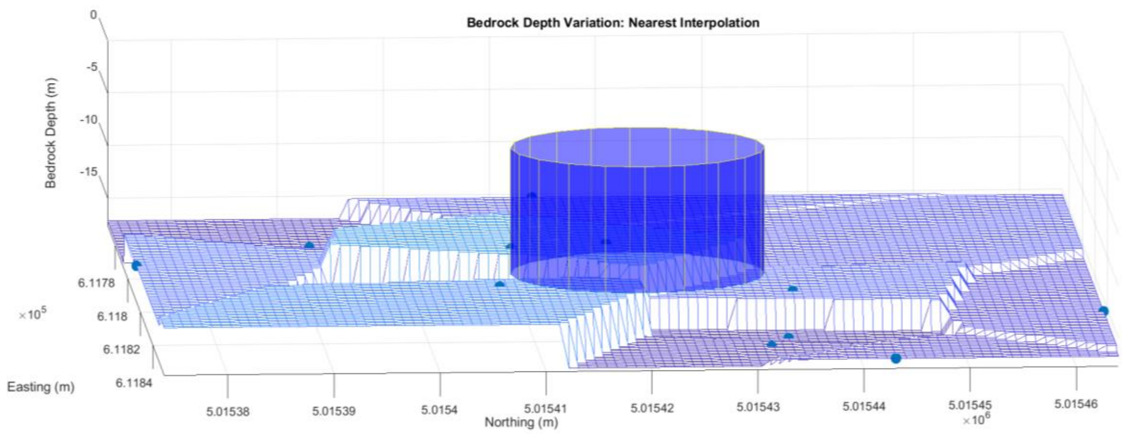

Figure 10. Bedrock depth estimates around sinkhole S001, looking west.

4. Conclusions

Evaluations of HVSR data collected by the GEER team following the December 2020 Petrinja earthquake in Croatia has been performed to gain an understanding of the site resonant frequencies in the area around Sinkhole S001. The primary goal was to assess whether the HVSR measurements can provide a reasonable estimate of depth to competent rock and the potential location of karst features which are common in the area where the measurements were obtained. Additionally, the presented results are novel from the perspective of complexity of interpretation and analysis of HVSR measurement in karst rock, which is typically weathered and contains numerous voids, dry and saturated fluid flow channels.

The assessments incorporated sensitivity analyses of HSVR results to various factors including sampling frequency range and azimuthal variability. Analysis of the nanometrics data was performed using the web platform HVSRweb [5] as well as associated Python-based modules that are part of the hvsrpy package. Sensitivity analysis on azimuthal variability of the site resonant frequencies indicated a scatter in frequencies across azimuths from 0° to 180° for most of the sites. The variability was noted in both the site resonant frequencies as well as the standard deviation at each azimuth. Additionally, the sampling frequency range was varied to assess whether the results would indicate the presence of strong impedance contrasts at shallower depths consistent with potential depths of karst features. The median

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site resonant frequencies considering azimuthal variability based on resampling frequencies between 3 and 10 Hz indicated potential bedrock depths between 12.0 m and 18.0 m around S001, which is generally consistent with the bedrock depth assumed from the depth of the sinkhole. An evaluation of the spatial variability of the resonant frequencies around S001, and the corresponding depth estimates, also provided insight into potential presence and orientation of karst features around S001. A three-dimensional assessment of the estimated bedrock depth indicates several steep changes in upper karst horizon in several directions around the sinkhole area which may indicate the presence of voids or karst. The steep changes appear to be oriented in the southwest-northeast direction and may offer an indication of the location of voids which may have facilitated development of Sinkhole S001 following the earthquake. Based on the assessed data, HVSR data from nanometrics measurements appears to be a useful tool for assessing variations in subsurface impedance contracts and can be used to augment geotechnical data and other geophysical measurement techniques due to the relative ease of deployment and rapid data acquisition.

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