DOI: https://doi.org/10.3986/ac.v52i1.10987

CHARACTERISTICS OF KARST CAVES INFERRED FROM MICROTREMOR STUDIES: A CASE STUDY FROM CERME CAVE, YOGYAKARTA, INDONESIA

ZNAČILNOSTI KRAŠKIH JAM, ZBRANE NA PODLAGI RAZISKAV MIKROTREMORJEV: ŠTUDIJA PRIMERA JAME CERME, YOGYAKARTA, INDONEZIJA

Gatot YULİYANTO[1*] & Muhammad Irham NURWİDYANTO[2]

Abstract UDC 551.442:550.34(594)

Gatot Yuliyanto & Muhammad Irham Nurwidyanto: Characteristics of karst caves inferred from microtremor studies: A case study from Cerme Cave, Yogyakarta, Indonesia

A microtremor survey based on ground surface data acquisition was used to identify and characterize the karst area of Cerme Cave, Yogyakarta, Indonesia, from the entrance to the exit of the cave. The entrance and exit of the cave are used as tie-in points because the characteristics of the two locations can be directly observed. Parameters used in this study include ground vibration amplification, shear wave velocity, and Poisson's ratio. The presence of cavities can be characterized by a relatively strong contrast between these physical parameters and their surroundings. The exit of the cave, which can be considered as a sinkhole, has a dominant frequency of 3.2 to 4.6 Hz, which is relatively higher than that of the surrounding area. At the entrance of Cerme Cave, which has a large cavity, a small ground vibration amplification was detected, less than 0.1. The entrance and exit of the cave also exhibit a low shear wave propagation velocity of less than 350 m/s. The presence of a subsurface fluvial channel in Cerme Cave can be characterized by a high Poisson's ratio of 0.4–0.5, a gain value of less than 0.1, and a shear wave velocity of less than 350 m/s.

Keywords: microtremor, karst, Cerme Cave, amplification, Poisson's ratio.

Izvleček UDK 551.442:550.34(594)

Gatot Yuliyanto & Muhammad Irham Nurwidyanto: Značilnosti kraških jam, zbrane na podlagi raziskav mikrotremorjev: študija primera jame Cerme, Yogyakarta, Indonezija

Raziskava mikrotremorjev, ki temelji na pridobivanju podatkov o površini tal, je podlaga za opredelitev in opis kraškega območja jame Cerme v Yogyakarti v Indoneziji, in sicer od vhoda v jamo do izhoda iz nje. Vhod v jamo in izhod iz nje sta uporabljena kot povezni točki, saj je mogoče značilnosti obeh lokacij opazovati neposredno. Parametri, uporabljeni v tej študiji, vključujejo okrepitev vibracij tal, hitrost strižnega valovanja in Poissonovo razmerje. Prisotnost votlin je mogoče opredeliti z razmeroma močnim kontrastom med temi fizikalnimi parametri in njihovo okolico. Izhod iz jame, ki se lahko obravnava kot vrtača, ima prevladujočo frekvenco od 3,2 do 4,6 Hz, ki je razmeroma višja od frekvence okolice. Na vhodu v jamo Cerme, kjer je velika votlina, je bilo zaznano majhna okrepitev vibracij tal, tj. manjša od 0,1. Na vhodu v jamo in izhodu iz nje je tudi majhna hitrost širjenja strižnega valovanja, tj. manjša od 350 m/s. Prisotnost podzemnega rečnega kanala v jami Cerme je mogoče opredeliti z visokim Poissonovim razmerjem 0,4 do 0,5, vrednostjo okrepitve manj kot 0,1 in hitrostjo strižnega valovanja manj kot 350 m/s.

Ključne besede: mikrotremor, kras, jama Cerme, okrepitev, Poissonovo razmerje.

[1] Department of Physics, Faculty of Science & Mathematics, Diponegoro University, Semarang, Central Java, Indonesia, e-mail: gatoty@fisika.fsm.undip.ac.id

[2] Department of Physics, Faculty of Science & Mathematics, Diponegoro University, Semarang, Central Java, Indonesia, e-mail: irhammn@lecturer.undip.ac.id

* Corresponding author

Prejeto/Received: 24. 1. 2022

1. INTRODUCTION

In general, exploring the presence of subsurface cavities in karst areas is difficult and risky. For geophysical methods, this remains one of the greatest challenges to date, as tools with high power and resolution must be used to image models with good resolution of hollow subsurface layers with irregular cavity geometry. In many cases, the subsurface cavities of karst areas contain water and/or air, so the subsurface cavities do not produce easily detectable geophysical anomalies despite the significant difference in the physical properties of the rock relative to the surrounding rock.

Currently, several geophysical methods are used to determine the location of subsurface voids, including ground penetrating radar (GPR) (Azimah & Widodo, 2017), resistivity method (Vargemezis et al., 2007; Hamdan et al., 2012), gravity (Braitenberg et al., 2016), magnetometry (Gibson & George, 2004), electromagnetic (Huang et al., 2020), seismic (Polymenakos, 2017), and Self Potentials (Vichabian & Morgan, 2002). However, due to geological factors, the size, shape, and orientation of subsurface voids, these methods have limitations in terms of penetration depth and resolution accuracy. In addition, gravity methods and seismic methods require a long data acquisition time and are quite expensive. In many cases, a single geophysical method for identifying subsurface cavities in karst areas cannot produce a conclusive and reliable result. No single geophysical method is capable of identifying subsurface voids with good results; it is common to use more than one geophysical technique to improve the reliability of the resulting interpretation. For example, combined resistivity methods with gravity (Hartvich & Valenta, 2011; Putiska et al., 2014), resistivity and LiDAR (Kasprzak et al., 2015; Stafford et al., 2107), resistivity and seismic refraction (Valois et al., 2010), resistivity and magnetism (Balkaya et al., 2012), electromagnetic and GPR (Pueyo et al., 2017), combined methods of Surface Nuclear Magnetic Resonance (SNMR), seismic refraction and seismic reflection, Transient Electromagnetic (TEM), Multichannel Analysis of Surface Waves (MASW), microgravity and magnetic surveys and their combinations (Ezersky et al., 2017), and an integrated survey using Ground Penetrating Radar (GPR), Electrical Resistivity Tomography (ERT), and Very Low-Frequency Electromagnetic (VLF-EM) methods (Hussain et al., 2020).

In the last decade, passive seismic methods that use ambient noise or microtremor methods have rapidly evolved. A microtremor is a low-amplitude vibration of about 0.1-1 microns with an amplitude velocity of 0.0001-0.01 cm/s near the ground caused by various natural factors such as wind, ocean waves, vehicle noise, and others (Mirzaoglu & Dykmen, 2003). The concept of the microtremor was introduced by Omori in 1908 and later further developed by Kanai and Tanaka in 1961. In 1970, Nogoshi and Igarashi introduced a technique using the horizontal to vertical spectral ratio of microtremor (HVSR), which was later used by Nakamura (1989) to estimate resonance frequency and local geologic amplification factors. The horizontal-to-vertical spectral ratio (HVSR) is defined as follows:

$$\left(H/V\right) = \sqrt{\frac{S^2{}_{NS} + S^2{}_{EW}}{S^2{}_{UD}}} \quad (1)$$

S_{UD} is the Fourier amplitude spectrum of the vertical component of the microtremor; S_{NS} and S_{EW} are two orthogonal horizontal components [1]. The HVSR microtremor method is also known as the single-station microtremor method. Data acquisition using this method can be performed quickly, easily, and relatively inexpensively (Sasongko et al., 2000). In its development, this method has been widely used in geotechnical and environmental fields. Some of them are correlation of microtremor measurement results with local geological conditions (Fabrizio et al., 2008), soil and building vulnerability studies, soil shear stresses and sliding surfaces of landslide movements (Yuliyanto et al., 2016, 2017, 2018; Sasongko et al., 2020), subsidence studies (Widada et al., 2019), buried objects studies such as archaeological objects (Yuliyanto, 2020; Ubaidillah et al., 2020). On the other hand, the use of microtremor methods for subsurface cavity detection is still relatively small, some of which are studies of caves in coastal areas using microtremor arrays (Nagao et al., 2017), physical modelling and field experiments for subsurface cavity detection (Kolesnikov & Fedin, 2017), and combined methods employing resistivity with microtremors for small caves (Nehme et al., 2013).

To determine how the microtremor method responds to the presence of voids below the ground surface with a vertical structure model, several preliminary studies were conducted, including by Justin et al. (2022), who used formerly dug wells and bunker seismometers located on the Diponegoro University campus and successfully obtained void spectrum responses with reasonably good sensitivity. In addition, the response characteristics of sinkholes in karst areas were investigated using the microtremor method of Delfira et al. (2022), and the presence of sinkholes can be well imaged. Hana et al. (2021) used the presence of penstock pipelines as a continuous cavity model for the response of subsurface cavities with lateral structures and also obtained good response sensitivity with the microtremor method.

The parameters obtained from the HVSR microtremor data are amplification and the dominant frequency. The dominant frequency is closely related to the thickness of the sediment. The higher the frequency, the shallower the depth of the bedrock, and vice versa. The amplification value is related to the contrast ratio between the density of the surface layer and the underlying layer (Nakamura, 2000), and the peak of the curve represents the vertical lithological boundary. From the inversion of microtremor data, one of the elastic parameters of rocks can be extracted, namely Poisson's ratio (σ), which is one of the elastic moduli of rocks or subsurface layers. Poisson's ratio is a combination of Vp and Vs and can be described as follows (Lay & Wallace, 1995):

$$\sigma = \frac{V_p^2 - 2V_s^2}{2\left(V_p^2 - V_s^2\right)} \quad (2)$$

In general, the elastic parameters of rocks depend largely on their lithological properties, which include water saturation. In fluid media with zero stiffness, no shear wave can propagate, so the Poisson's ratio in the fluid is 0.5 (Schon, 2011). At constant pressure, Poisson's ratio increases with increasing water saturation and porosity. Some studies on using microtremors to identify the presence of subsurface layers with high water content such as aquifers include Yulianto et al. (2021), Yuliyanto et al. (2021), Gulo et al. (2022), and Nurwidyanto (2022). Based on the above description, the parameters of dominant frequency, amplification, shear wave velocity, and Poisson's ratio obtained by the microtremor method can be used to determine the physical characteristics of caves or cavities located beneath the surface of the soil layer.

2. STUDY AREA

Cerme Cave is located about 20 km south of Yogyakarta (Figure 1). The entrance of the cave is located in Srunggo, Selopamioro Village, Imogiri District, Bantul Regency, and the exit is located in Ploso area, Giritirto Village, Panggang District, Gunungkidul Regency. Topographically, Cerme Cave is a horizontal cave with a length of about 1.0 km and features the beauty of stalactites, stalagmites, underground rivers and waterfalls. The height of the cave ceiling varies from 1 to 20 meters. Cerme Cave is the main cave, which houses several small caves. The interior of the cave is completely dark and the floor is flooded with groundwater that regularly rises and falls during the rainy season and recedes during the dry season.

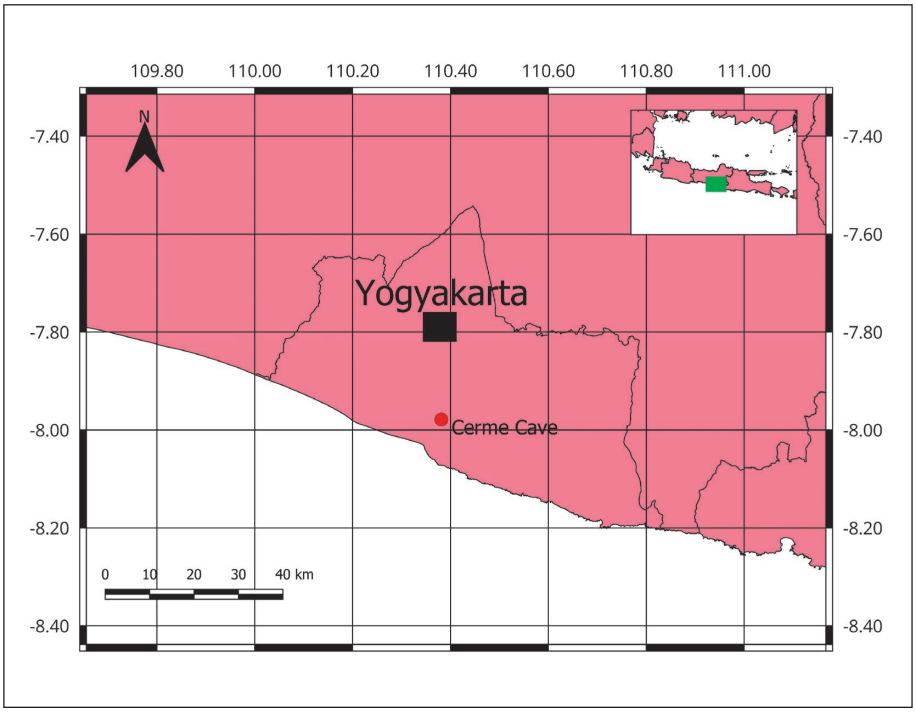

Figure 1: Location of Cerme Cave, marked with a red circle, located about 20 km south of Yogyakarta.

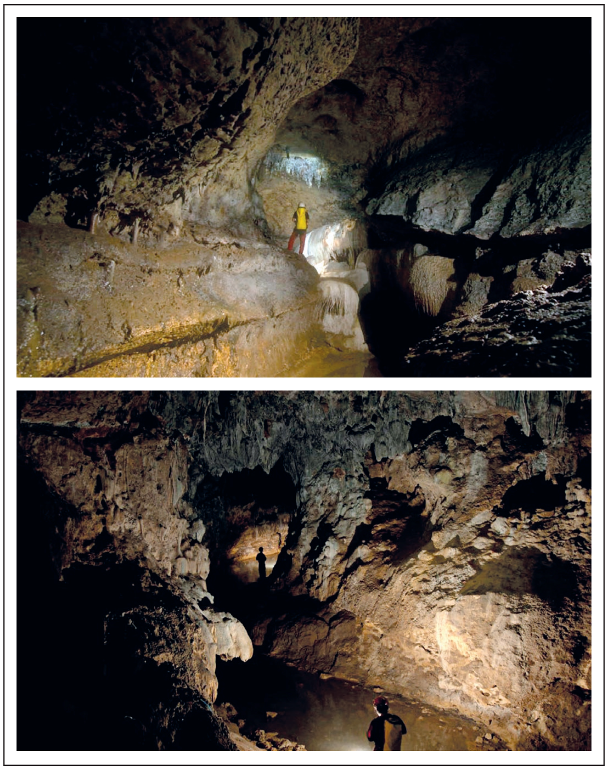

Figure 2: Part of the chambers inside the Cerme Cave (http://asc.or.id/asc-jogja/cave-tourism-2-cerme).

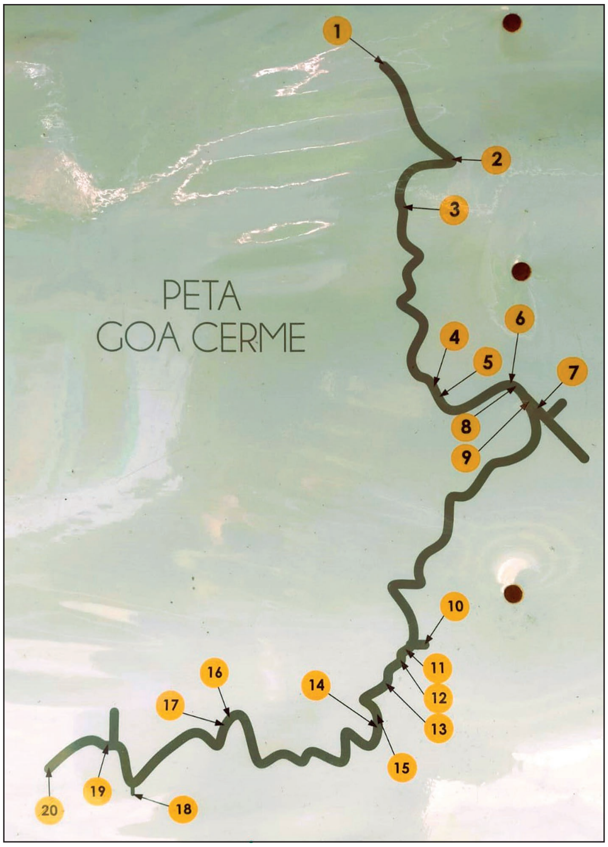

Figure 3: A ground plan of Cerme Cave with no scale attached to the information board in front of the cave. Based on this ground plan, number 1 is the location of entrance of the cave and number 20 is the exit of the cave. Numbers 7, 14, and 19 are small caves inside Cerme Cave.

The Cerme Cave is part of the karst area of the Sewu Mountains. The rocks in this karst area consist of coralline limestones clustered in the Wonosari Formation and clastic limestones with marl fillings belonging to the Oyo Formation. Both limestones are estimated to be about 5.3 million years old (middle Miocene–Pliocene). Physically, the reef limestone has a rough surface, while the clastic limestone, which is generally hollow, has a dense, impermeable limestone layer. An example of part of the chambers in Cerme Cave is shown in Figure 2.

The literature search conducted revealed that there is no research that examines Gua Cerme based on field geophysical studies. The existing studies are more related to areas in Gunung Kidul or Gunung Sewu where the Cerme Cave is located. One of them is Haryono and Hari (2004), who conducted a landscape differentiation study based on surface observations in Gunung Kidul karst.

To date, it has not been possible to obtain a base map or floor plan of the Cerme Cave based on previous studies. There are no speleological reference maps or ground plans of Cerme Cave that can be used in this study. There is only a ground plan of Cerme Cave without scale, which is attached to the information board in front of the cave (Figure 3). There is no information about the method used to create the plan.

3. MICROTREMOR SURVEY

Data acquisition with the microtremor method was performed at 46 stations (Figure 4) using 4 portable seismometer units with VHL PS-2B 2 Hz triaxial geophones and 3 Graphtec GL 240 data loggers and 1 Graphtec GL 840 data logger. The duration of microtremor vibration recording at each station was 20 minutes with a sampling rate of 50 ms. In the subsequent data processing, the vibration data at each station, which is still in the time domain, is converted to a frequency domain. Then the horizontal components are compared with the vertical

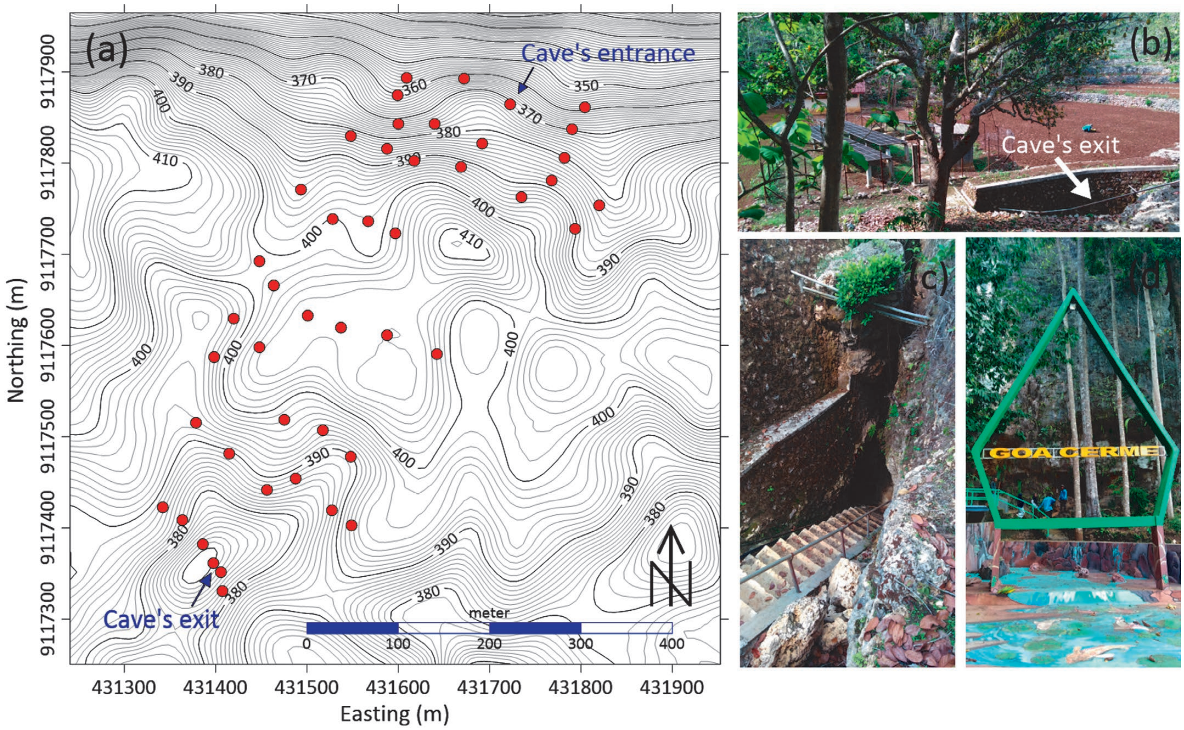

Figure 4: (a) Microtremor measurement stations (red circle) and measurement trajectory (blue line), (b) situation around the cave's exit area, (c) location of the cave's exit, (d) Cerme Cave's entrance situation.

component and the HVSR curve, i.e., the amplification curve to frequency, is obtained using Geopsypack-2.5.0 software. To obtain the velocity of longitudinal waves (Vp) and the velocities of shear waves (Vs) propagating in the subsurface layer, and the density of the propagation medium, the data were inverted using Vs Dinver Ver 0.5.4 software. The settings in this inversion software include the following: the amount of soil layer, the thickness or depth of the soil layer, the longitudinal wave velocity (Vp), the shear wave velocity (Vs), and the Poisson's ratio (σ). The result of the inversion at each measurement station is the value of the compressional wave velocity and the shear wave velocity for a given soil thickness.

The cave's entrance and cave's exit serve as reference stations, since both are features that can be observed directly from the ground level. The response spectra and inverse data from both gates are used as forward models to bind responses and compare them with other stations. For this reason, cross-sectional profiles of longitudinal wave velocity (Vp), shear wave velocity (Vs), and Poisson's ratio (σ) passing through both gates are created.

4. RESULTS AND DISCUSSION

To determine the characteristics of the HVSR curves at the cave's exit and above the cave's entrance, measured near the ground level, the HVSR curves at both cave's gates are compared with several other stations (Figure 5). Stations with measurement trajectories crossing the cave's exit are coded with the alphabetical prefix A, while stations crossing the cave entrance are coded H. Stations A5 and A6 are measurement stations located near the cave's exit, while station H3 is located directly above the cave's entrance. It can be seen that the HVSR curves at the cave's exit and entrance have amplification values below 0.1, which is much lower than the ground vibration amplification of the HVSR curves at other stations. This low amplification appears throughout the frequency range of the HVSR curve.

To determine the response of the microtremor spectrum to lateral depth from Figure 5, the response spectrum, shear wave velocity, and Poisson's ratio profiles are arranged based on the station sequence, as shown in Figure 6. Both cave entrances appear to have a pattern of spectral response values less than 1 Hz. Near the cave exit, there is considerable anomaly amplification at frequencies above 5 Hz. According to local residents, water collects under the rock layer east of the cave exit from various directions, becoming a single source of water that then flows to the cave entrance at a lower elevation.

The presence of a vibration amplification value of less than 1 may indicate damping of the energy by diffusive reflection of the vibration energy in the cave cavity due to the morphology, geometry of the cave, and rocks in the cave. The extreme amplification anomaly due to attenuation and absorption of vibrational energy near the bottom of the cave exit is likely due to the water source in the cave, in addition to the morphology, geometry, and rocks that make up the cave.

To determine the hardness of the rock, the value of the shear wave velocity (Vs) can be used as a parameter. In this case, SNI 1726-2019 is used as a reference standard. Hard rock sites have Vs above 1500 m/s, medium-hard rock sites have Vs between 750-1500 m/s, hard, firm, low-hard rock sites have Vs 350-750 m/s, medium-hard soil sites have Vs 175-350 m/s, and soft soil sites

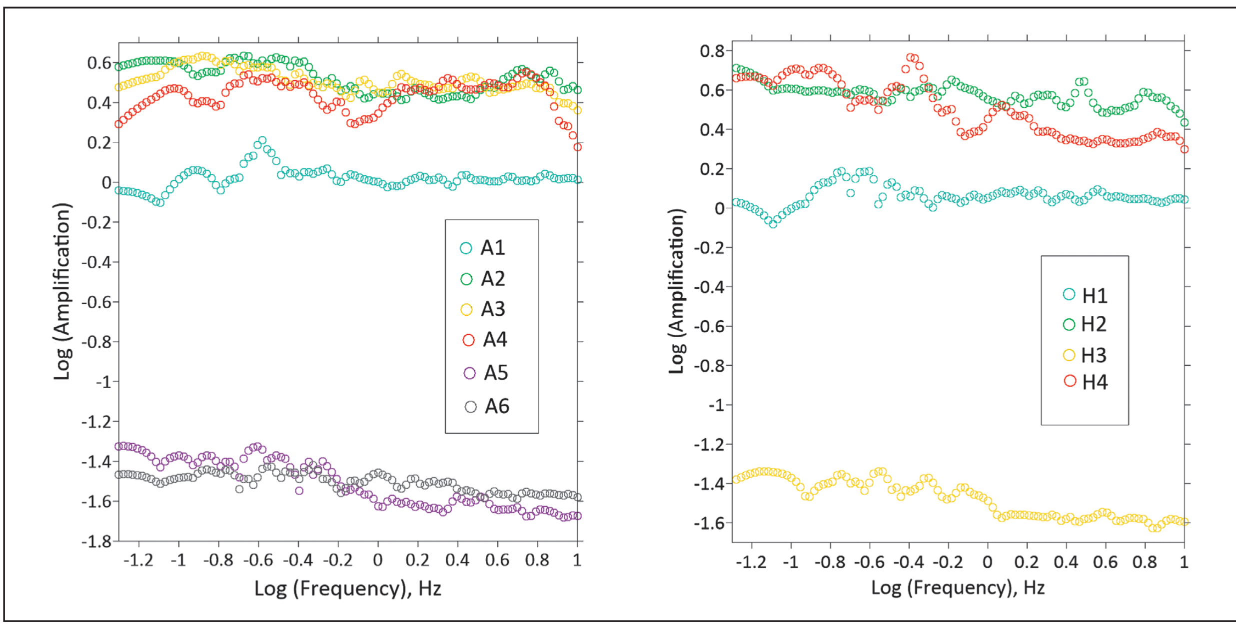

Figure 5: The HVSR curve on the measurement path passing through the cave exit, encoded with the alphabetical prefix A (left) and the one passing through the cave entrance is encoded with the alphabetical prefix H (right). The HVSR curves of both cave gates have amplification values below 0.1, which is much lower than amplification at other stations.

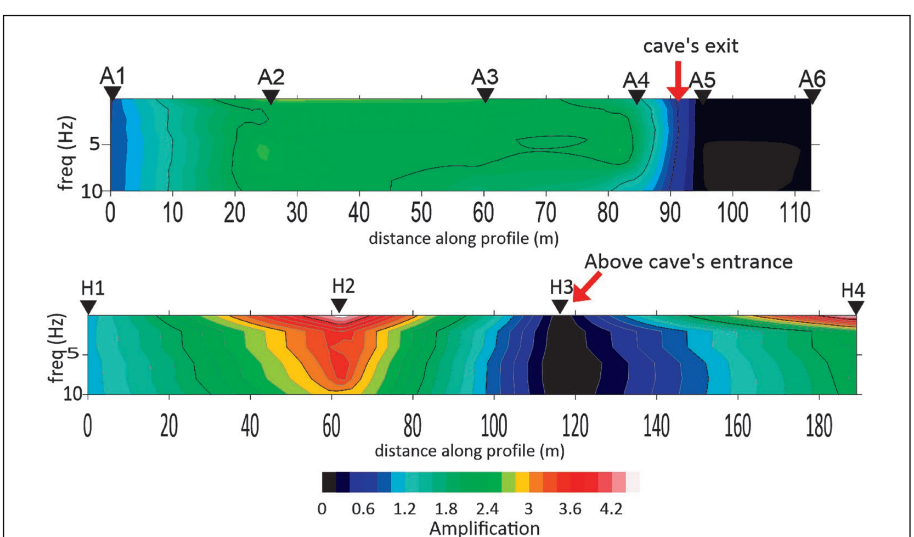

Figure 6: Spectral response profile for station trajectories passing through the cave exit (top) and passing through the cave entrance (bottom). Both caves have an amplification value of less than 1.

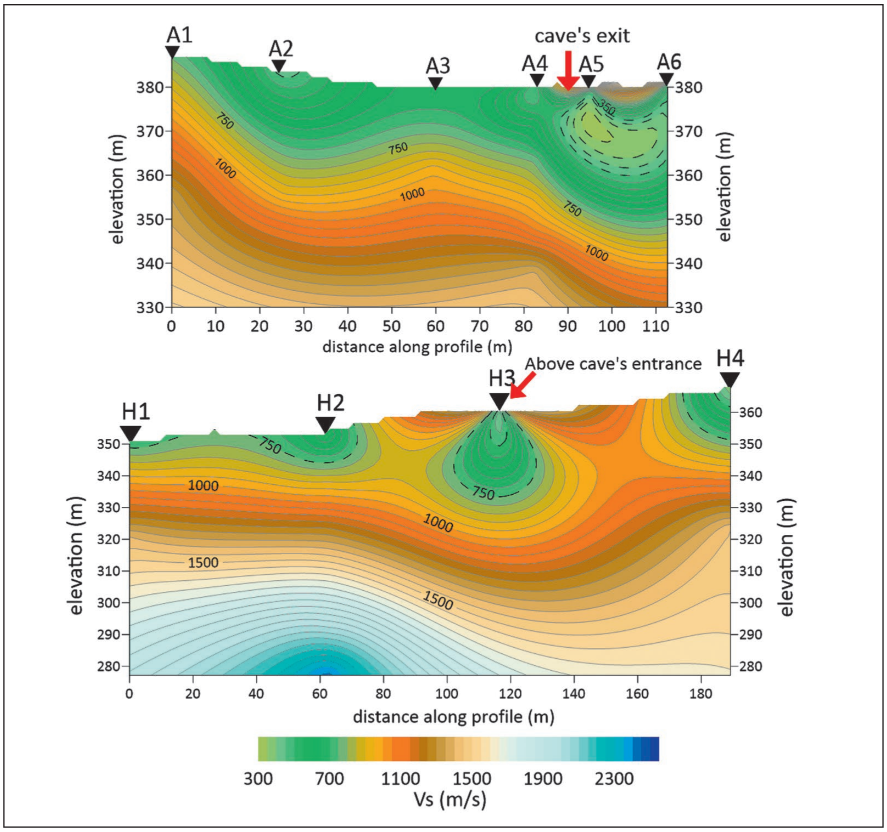

Figure 7: Shear wave velocity profile. The cave entrance is characterized by a low shear wave velocity below 350 m/s (top). The contour above the cave's entrance shows a layered pocket-like loop pattern with less than 750 m/s (bottom).

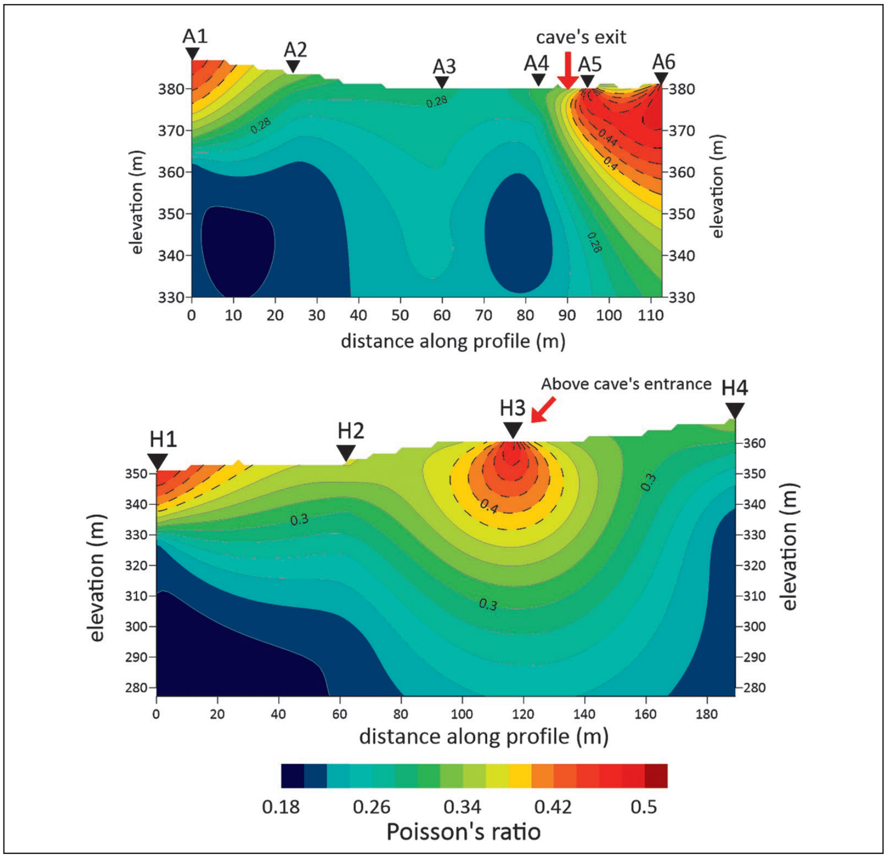

Figure 8: Poisson's ratio profile for measurement trajectories passing through the cave's exit (top) and those passing through the cave's entrance (bottom). Both cave gates have higher Poisson's ratio values than Poisson's ratio values at other stations.

have Vs below 350 Vs m/s. A shear wave velocity profile with the same trajectory as in Figure 6 is shown in Figure 7. The shear wave velocity in the rock layer around the cave exit is 750-1800 m/s. Below this rock layer is a soil layer with Vs 128-750 m/s, with the lowest Vs at the spring site below the cave exit. The low Vs is probably due to the fluid filling the rock pores and the spaces between the rock fragments at this location.

The study area had a Poisson's ratio value of 0.18-0.5 (Figure 8). According to Gercek (2007), the value of Poisson's ratio of limestone ranges from 0.11 to 0.33, indicating that the Poisson's ratio is suitable for field conditions. In the area of the cave exit, there is a high Poisson's ratio value of 0.4-0.5 at a depth of 20 m below the surface. Based on observations in the field, a water source was found at this depth, on the inside of the cave's

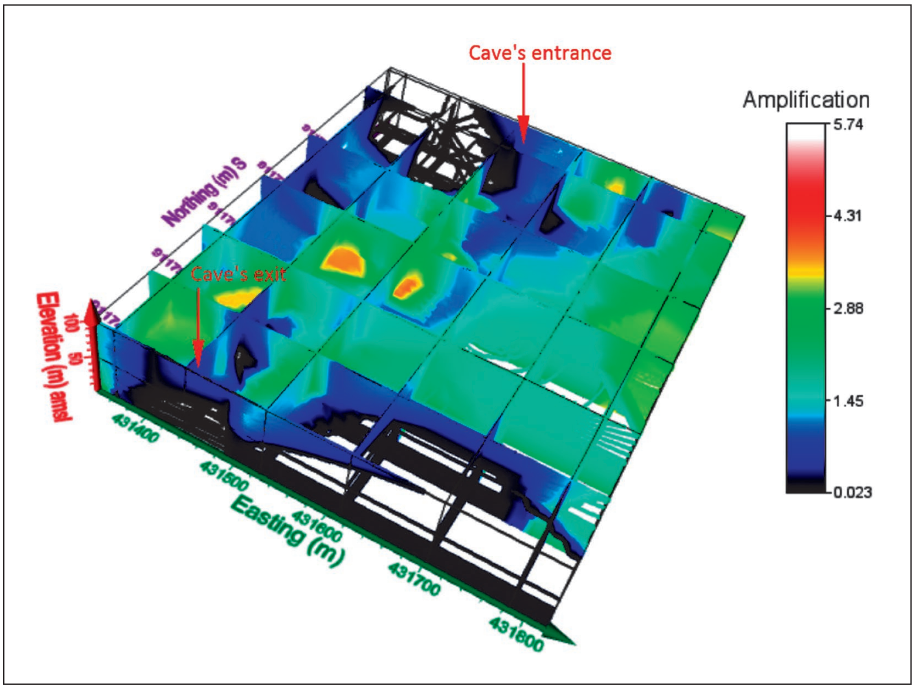

Figure 9: Model of the trajectory of the underground river flow inside Cerme Cave. The poor contour pattern located at the top right and bottom right is caused by the absence of data in this section.

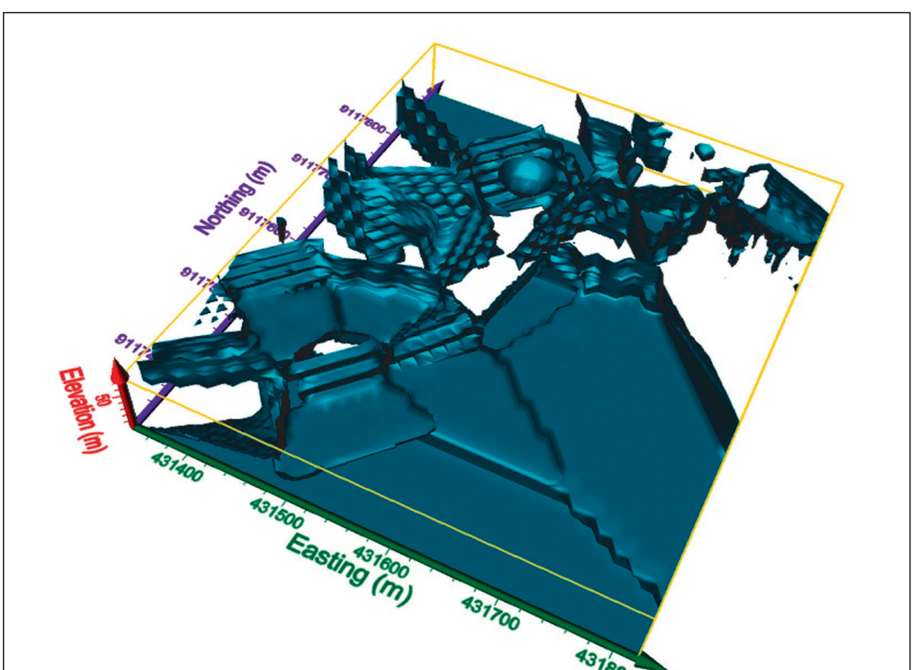

Figure 10: Model of 3D isosurface based on Figure 9, which shows the existence of a pattern of cavities in Cerme Cave. The isosurface value used in this model is 0.6.

exit. At the measurement site above the cave's entrance, a Poisson's ratio value of 0.4-0.5 was recorded at a depth of 27 m. This correlates with the response spectrum profiles in Figures 5 and 6, which show a low ground vibration amplification. In addition, a longitudinal section of the ground vibration amplification model with very low vibration amplification can be interpreted as an underground river flow passage inside Cerme Cave, as shown in Figure 9. To confirm the interpretation of Figure 9, a 3D model of the 0.6 amplification isovalues can be interpreted as the presence of subsurface cavities (Figure 10).

5. CONCLUSIONS

Surface surveys can effectively use microtremor methods to characterize and identify subsurface cavities in Cerme Cave. This method can be effectively used as a standalone method to confirm cave's features of Cerme Cave, such as cave entrances and exits, as well as to identify possible cave cavities located below the surface. The presence of cavities represented by cave's exits in the Cerme Cave karst area can be characterized by a high contrast of the dominant frequency of ground vibrations with a characteristic frequency of 3.2-4.6 Hz. The characteristics of the large cavities in Cerme Cave show a low ground vibration amplification, less than 0.1. The possibility of an underground river channel in Cerme Cave can be characterized by a high Poisson's ratio of 0.4-0.5 and a low shear wave velocity of less than 350 m/s.

ACKNOWLEDGEMENTS

We would like to thank Diponegoro University for supporting this research under the 2020 RPP program.

REFERENCES

Arai, H., Tokimatsu, K., 1998. Evaluation of local site effect based on microtremor H/V spectra. The Effect of Surface Geology on Seismic Motion, Balkema, Rotterdam.

Azimmah, A., Widodo, 2017. Analysis of Ground Penetrating Radar's Capability for Detecting Underground Cavities: A Case Study in Japan Cave of Taman Hutan Raya, Bandung. IOP Conf. Series: Earth and Environmental Science. 62-012030. https://doi.org/10.1088/1755-1315/62/1/012030.

Balkaya, C., Göktürkler, G., Erhan, Z., Ekinci, Y.L., 2012. Exploration for a cave by magnetic and electrical resistivity surveys: Ayvacık Sinkhole example, Bozdağ, İzmir (western Turkey). GEOPHYSICS. 77.3. https://doi.org/10.1190/geo2011-0290.1.

Braitenberg, C., Sampietro, D., Pivetta T., Zuliani, D., Barbagallo, A., Fabris, P., Rossi, L., Fabbri, J., Mansi, A.H., 2016. Gravity for Detecting Caves: Airborne and Terrestrial Simulations Based on a Comprehensive Karstic Cave Benchmark. Pure and Applied Geophysics. 173: 1243–1264.

Delfira, Yuliyanto, G., Nurwidyanto, MI., 2022. Characterization of Sinkhole in Ngrombo, Bedoyo, Ponjong, Gunung Kidul Indonesia with the Horizontal to Vertical Spectral Rasio Microtremor Method, Journal of Research in Environmental and Earth Sciences, 8(12): 01-05.

Ezersky, M.G., Legchenko, A., Eppelbaum, L., Al-Zoubi, A., 2017. Overview of the geophysical studies in the Dead Sea coastal area related to evaporite karst and recent sinkhole development. International Journal of Speleology, 46 (2): 277-302. https://doi.org/10.5038/1827-806X.46.2.2087.

Fabrizio, C., Cultrera, G., Azzara, RM., Valerio, DR., Giuseppe, DG., Giammarinaro, MS., Tosi, P., Vallone, P., Rovelli, A., 2008. Microtremor Measurements in the City of Palermo, Italy: Analysis of the Correlation with Local Geology and Damage, Bulletin of the Seismological Society of America, 98 (3): 1354-1372.

Gercek, H., 2007. Poisson's ratio values for rocks. International Journal of Rock Mechanics and Mining Sciences, 44(1): 1–13. https://doi.org/10.1016/j.ijrmms.2006.04.011.

Gibson, P.J., Lyle P., George M., 2004. Application of resistivity and magnetometry geophysical techniques for near-surface investigations in karstic terranes in Ireland. Journal of Cave and Karst Studies, 66 (2): 35-38.

Gua Cerme Yogyakarta. http://asc.or.id/asc-jogja/cave-tourism-2-cerme [accessed June 14, 2020].

Gulo, TS., Yuliyanto, G., Harmoko, U., 2022. Identification of the aquifer layers using HVSR method in Tosoro, Semarang Regency, Central Java, Indonesia. Journal of Research in Environmental and Earth Sciences, 8(6): 5-56.

Hamdan. H., Economou, N., Kritikakis, G., Andronikidis, N., Manoutsoglou, E., Vafidis, A., Pangratis, P., Apostolidou, G., 2012. 2D and 3D imaging of the metamorphic carbonates at Omalos plateau/polje, Crete, Greece by employing independent and joint inversion on resistivity and seismic data. International Journal of Speleology, 41(2): 199-209. http://dx.doi.org/10.5038/1827-806X.41.2.7.

Hana, N., Yuliyanto, G., Nurwidyanto, MI., 2021. Identification of the PLTA Jelok Tuntang rapid pipeline (penstock) based on the spectra response of the microtremor method. IOSR Journal of Applied Geology and Geophysics, 9(5): 41-48.

Hartvich, F., Valenta, J., 2011. The identification of faults using morphostructural and geophysical methods: a case study from Strašín cave site. Acta Geodyn. Geomater., 8(4 -164): 425–441.

Haryono, E., Day, M., 2004. Landform differentiation within the Gunung Kidul Kegelkarst, Java, Indonesia. Journal of Cave and Karst Studies, 66(2): 62-69.

Huang, S., Lin, J., Huang, Q., Liang, R., 2020. An emerging method using Electromagnetic wave computed tomography for the detection of karst caves. Geotechnical and Geological Engineering, 38: 2713–2723.

Hussain, Y., Uagoda, R., Borges, W., Nunes, J., Hamza, O., Condori, C., Aslam, K, Dou, J., Cárdenas-Soto, M., 2020. The potential use of geophysical methods to identify cavities, sinkholes and pathways for water infiltration. Water, 12(8): 2289; doi:10.3390/w12082289.

Justin, AFA., Yuliyanto, G., Harmoko, U., 2022. Sensitivity to the Presence of Subsurface Cavities From Microtremor Response Data. International Journal of Engineering Science Invention (IJESI) 11(6): 27-31.

Kasprzak, M., Sobczyk, A., Kostka S., Haczek A., 2015. Surface geophysical surveys and LiDAR DTM analysis combined with underground cave mapping–an efficient tool for karst system exploration: Jaskinia Niedzwiedzia case study (Sudetes, SW Poland). Geomorphometry for Geosciences, Jasiewicz J., Zwolinski Zb., Mitasova H., Hengl T. (eds), 2015. Adam Mickiewicz University in Poznan Institute of Geoecology and Geoinformation, International Society for Geomorphometry, Poznan.

Keceli, A., 2012. Soil parameters which can be determined with seismic velocities. Jeofizik, 16: 17-29.

Kolesnikov, Y.I., Fedin, K.V., 2017. Detecting underground cavities using microtremor data: physical modelling and field experiment. Geophysical Prospecting, 66(2): 342 – 353. https://doi.org/10.1111/1365-2478.12540.

Lay, T., Wallace T.C., 1995. Modern Global Seismology. Academic Press. San Diego California, USA.

Mirzaoglu, M., Dykmen, U., 2003. Application of Microtremor to Seismic Microzoning Procedure. Journal of The Balkan Geophysical Society, 6(3):143 – 156.

Nagao, T., Hakoda, T., Ito, Y., Yamada, M., Nishibata, K,, Tsuda, A., 2017. A fundamental study of a cave detection method in coastal area using microtremor array measurements. Journal of Japan Society of Civil Engineers Ser B3 (Ocean Engineering) 73(2):1450-1455. https://doi.org/10.2208/jscejoe.73.1-450.

Nakamura, Y., 1989. A Method for Dynamic Characteristics Estimations of Subsurface Using Mikrotremors on the ground Surface. QR RTRI, 30: 25-33.

Nakamura, Y., Sato, T., Nishinaga, M., 2000. Local Site Effect of Kobe Based on Microtremor Measurement. Proceeding of the Sixth International Conference on Seismic Zonation EERI, Palm Springs California.

Nehmé, C., Voisin, C., Mariscal, A., Gérard, P.C., Cornou, C., Jabbour-Gédéon, B., Amhaz, S., Salloum, N., Badaro-Saliba ,N., Adjizian-Gerard, J., Delannoy, J.J., 2013. The use of passive seismological imaging in speleogenetic studies: an example from Kanaan Cave, Lebanon. International Journal of Speleology, 42(2): 97-108. Tampa, FL (USA) ISSN 0392-6672 http://dx.doi.org/10.5038/1827-806X.42.2.1.

Nogoshi, M., Igarashi, T., 1971. On the amplitude characteristics of microtremor (Part 2). Jour. seism. Soc. Japan, 24: 26-40 (in Japanese with English abstract).

Nurwidyanto, MI., Yuliyanto, G., 2022. Application of the HVSR Microtremor Method for Groundwater Aquifer Identification: Case study in Pencitrejo, Terong Village, Dlingo, Bantul, Yogyakarta, Indonesia. Journal of Research in Environmental and Earth Sciences, 8(6): 20-23.

Polymenakos, L., 2017. Investigation of clay sediments and bedrock morphology in caves with seismic traveltime tomography: an application at Alepotrypa Cave (Diros, Greece). International Journal of Speleology, 46(1): 1-12. Tampa, FL (USA) ISSN 0392-6672 https://doi.org/10.5038/1827-806X.46.1.2005.

Pueyo, A.Ó., Juan, P.A., Sainz, C.A.M., Abadías, J.G., Carrera H.D.L., 2017. Integrated approach for sinkhole evaluation and evolution prediction in the Central Ebro Basin (NE Spain). International Journal of Speleology, 46(2): 237-249. https://doi.org/10.5038/1827-806X.46.2.2064.

Putiska, R., Kusnirak, D., Dostal, I., Lacny, A., Mojzes, A., Hok, J., Pasteka, R., Krajnak, M., Bosansky M., 2014. Integrated geophysical and geological investigations of karst structures in Komberek, Slovakia. Journal of Cave and Karst Studies, 76(3):155–163.

Sasongko, D.P., Yuliyanto, G., Arifin, Z., 2019. Vibration vulnerability identification in Kota Lama Semarang using Microtremor Method. Indonesian Journal of Applied Physics, 9 (2): 105-111. https://doi.org/10.13057/ijap.v9i02.34592.

Sasongko, D.P., Yuliyanto, G., Arifin, Z., 2020. Karakterisasi Daerah Rawan Gerakan Tanah di Lapangan Pandanmurti Desa Candigaron Kecamatan Sumowono Kabupaten Semarang dengan Metode Mikrotremor. Jurnal Pembangunan Wilayah & Kota, 16(2): 136-143. https://doi.org/10.14710/pwk.v16i2.26401.

Schon, J.H., 2011. Physical properties of rocks. Elsevier, 228-231. http://sispk.bsn.go.id/sni/DetailSNI/12762. accessed April 4, 2023, at 14:08

Stafford, K.W., Brown, W.A., Ehrhart, J.T., Majzoub A.F., Woodard, J.D., 2017. Evaporite karst geohazards in the Delaware Basin, Texas: review of traditional karst studies coupled with geophysical and remote sensing characterization. International Journal of Speleology, 46 (2): 169-180. https://doi.org/10.5038/1827-806X.46.2.2089.

Ubaidillah, M.A., Yuliyanto, G., Irham, M.N., 2020. Delineation of the new site of Ngempon Temple in Ngempon Village, Bergas District, Semarang Regency using the microtremor method. Journal of Physics: Conference Series 1524 (2020) 012017. https://doi.org/10.1088/1742-6596/1524/1/012017.

Valois, R., Bermejo, L., Guerin, R., Hinguant, S., Pigeaud, R., Rodet, J., 2010. Karstic Morphologies Identified with Geophysics around Saulges Caves (Mayenne, France). Archaeol. Prospect 17:151–160. https://doi.org/ 10.1002/arp.385.

Vargemezis, G., Tsourlos, P., Papazachos, C., Kostopoulos, D., 2007. Application of electrical resistivity Tomography to the detection of the Ermakia (Northern Greece) cavity system. Bulletin of the Geological Society of Greece vol. XXXX, 2007. Proceedings of the 11th International Congress, Athens, May, 2007.

Vichabian, Y., Morgan F. D., 2002. Self Potentials in Cave Detection. The Leading edge. 21(9). https://doi.org/10.1190/1.1508953.

Widada, S., Zainuri, M., Yuliyanto, G., Yulianto, T., Sugianto, D.N., 2019. Identification ground layer structure of land subsidence sensitive area in Semarang City with horizontal to vertical spectral rasio method. IOP Conf. Series: Earth and Environmental Science 246 – 012023. https://doi.org/10.1088/1755-1315/246/1/012023.

Yuliyanto, G., Harmoko, U., Widada, S., 2016. Identification of Potential Ground Motion Using the HVSR Ground Shear Strain Approach in Wirogomo Area, Banyubiru Subdistrict, Semarang Regency. International Journal of Applied Environmental Sciences 11 (6): 1497-1507.

Yuliyanto, G., Harmoko, U., Widada, S., 2017. Identify the slip surface of land slide in Wirogomo Banyubiru Semarang Regency using HVSR method. International Journal of Applied Environmental Sciences 12 (12): 2069-2078.

Yuliyanto, G., Harmoko, U., Indriana, R.D., 2018. Identification of Landslide Area in JabunganVillage, Banyumanik, Semarang using Microtremor Method. International Journal of Recent Trends in Engineering & Research (IJRTER) 04(05): 129-137.

Yuliyanto, G., Harmoko, U., Widada, S., 2019. Determination of bed rock depth using joint geoelectric and HVSR methods. IOP Conf. Series: Journal of Physics: Conf. Series 1217- 012039. https://doi.org/10.1088/1742-6596/1217/1/012039.

Yuliyanto, G., 2020. 3D modeling of buried site Ngempon Temple, Bergas, Semarang Regency using HVSR method. Journal of Physics: Conference Series 1524 (2020) 012050. https://doi.org/10.1088/1742-6596/1524/1/012050.

Yulianto, T., Sasongko, DP., Yuliyanto, G., Indriana, RD., Setyawan A., Widada, S. 2021. Correlation of Vp/Vs ratio against the resistivity value to determine the aquifers presence estimation in Jetak Subvillage, Getasan Sub-District, Semarang Regency. Journal of Physics: Conference Series, 1943 (2021) 012028. https://10.1088/1742-6596/1943/1/012028.

Yuliyanto, G., Nurwidyanto, MI., 2021. Integrated survey to identify potential groundwater aquifers in Jabungan Semarang using geoelectric and microtremor methods. Journal of Physics: Conference Series, 1943 (2021) 012026. https:// 10.1088/1742-6596/1943/1/012026.