

GEOHAZARD MAPPING WITH MICROTREMOR WAVES USING THE HVSR METHOD. CASE STUDY: SOUTHERN SEMARANG AREA, CENTRAL JAVA, INDONESIA

M. Irham NURWIDYANTO ^{1*}, Gatot YULIYANTO ¹ & Gregorius Alvin FERNANDO ¹

DOI: 10.21163/GT_2026.213.11

ABSTRACT

Semarang City is located in an area influenced by several active fault systems in Central Java, Indonesia. Semarang City has a historical record of being an area with relatively low seismic activity. Geological investigations and several recent sources of information indicate the presence of active faults around the city, thus increasing the potential for seismic hazards. This study aims to describe the potential seismic hazards in the southern part of Semarang using microtremor measurements analyzed through the Horizontal-to-Vertical Spectral Ratio (HVSR) method. Data collected in this study were 119 microtremor measurement stations placed to determine several location response parameters. The parameters used for analysis include the dominant frequency (f_0), amplification factor (A_0), seismic vulnerability index (SVI), Peak Ground Acceleration (PGA), and Ground Shear Strain (GSS). The results show that the dominant frequency value is influenced by the thickness of the sediment in a particular area. The South Semarang area has a dominant frequency value ranging from 0.13 to 9.21 Hz, with an average of 1.17 Hz at 119 microtremor stations. The amplification factor (A_0) values in the South Semarang region ranged from 0.53 to 6.94, with an average of 2.77. The seismic vulnerability index is used in seismic microzoning studies to map areas most at risk of structural damage due to geological conditions. The seismic vulnerability index in the South Semarang region ranged from 0.17 to 260.09 $\mu\text{cm}^2/\text{s}$, with an average of 32.29 $\mu\text{cm}^2/\text{s}$. Another calculation parameter used in this study was the PSDA (Deterministic Seismic Hazard Analysis) method, with PGA values in the South Semarang region ranging from 5.87 to 49.17 gal, with an average of 13.85 gal. The ground shear strain value affects post-earthquake conditions. The GSS value in the South Semarang region ranged from 1.3×10^{-5} to 3.59×10^{-4} , with an average of 1.3×10^{-4} . Spatial analysis shows that several sub-districts, particularly Tembalang, Banyumanik, and Pedurungan, have higher earthquake vulnerability than surrounding areas. Furthermore, more in-depth technical studies are needed in the geotechnical field in several locations with high seismic hazards (contained in the A_0 , f_0 , PGA, SVI, and GSS maps), and locations around faults in the Semarang area.

Keywords: A_0 ; F_0 ; SVI; PGA; GSS; Microtremor; Seismic.

1. INTRODUCTION

The geological conditions of Semarang City are situated at the intersection of alluvial plains (coastal) and volcanic hills, which are equipped with significant seismic potential due to the presence of active fault structures that cover Semarang City (Thanden et al., 1996). The comparison between the North Java and South Java faults lies in their activity, where the faults in North Java (including the Semarang City area) have a relatively low seismic activity. Based on historical records and geological studies, Semarang City is surrounded by significant active earthquake sources (Partono et al., 2018). Additionally, according to Newcomb and McCann (1987), the Central Java region has experienced several destructive earthquakes since the 19th century.

¹ Department of Physics, Faculty of Science and Mathematics, Diponegoro University, Semarang, Indonesia. Corresponding author: irhammn@lecturer.undip.ac.id (MIN); gatoty@fisika.fsm.undip.ac.id (GY); gregoriusalvinfernando@gmail.com (GAF).

Historical records show that there was an earthquake in 1867, which was thought to originate from a land fault (possibly from the Semarang fault or the Kaligarang fault), which caused severe damage to colonial buildings in Semarang and its surroundings, and caused many casualties. Other disasters that occurred in this city were local landslides and vibrations from the subduction zone (megathrust) in southern Java.

The presence of faults significantly increases the potential for earthquakes in the surrounding area because they act as weak zones in the Earth's crust and serve as reservoirs of tectonic energy (Scholz, 2019). As the Earth's plates continue to move, rocks along the fault planes interlock and rub against each other, causing mechanical stress to build up over time. This sudden, massive release of energy, which propagates to the surface in the form of seismic waves, can trigger earthquakes (Shearer, 2009). Because the rock structure in fault zones is fragile and has undergone deformation, this makes the area vulnerable to seismic activity. The presence of local faults that divide or are located near the Semarang area (Koesuma et al., 2022) increases the regional seismic risk, where even the slightest shift in a subsurface rock segment can trigger a shallow earthquake, the destructive power of which tends to be higher at the surface. This risk is exacerbated by the geological conditions of Semarang's environment, particularly in the northern part of Semarang and the lowlands, which are dominated by thick, incompletely compacted layers of alluvium or Quaternary sediment (Thanden et al., 1996). When seismic waves from the fault propagate through this soft soil layer, an amplification phenomenon occurs, where the amplitude of the earthquake waves actually increases, thereby amplifying the shaking felt at the surface.

Geotechnically, the presence of the Semarang Fault creates a shear zone that destabilizes the surrounding rock. This contributes to the high frequency of landslides in hilly areas such as Gombel and Candi. Furthermore, this fault activity also interacts with the land subsidence phenomenon in North Semarang (Marfai & King, 2007); although land subsidence is dominated by loading and groundwater extraction, the structural control of the Semarang Fault is believed to also influence the pattern of bedrock subsidence beneath the alluvium layer (Abidin et al., 2013).

Based on this, a method capable of explaining seismicity in Semarang is needed. The HVSR method, using microtremors, is one such geophysical method capable of explaining seismicity (Nurwidyanto et al., 2024; Simanjuntak et al., 2017). Microtremors are very subtle harmonic ground vibrations that occur continuously on the Earth's surface, while HVSR is a technique for analyzing microtremor data to obtain the physical characteristics of the soil. The parameters used in the HVSR method include dominant frequency, amplification factor, Seismic Vulnerability Index (Sasongko et al., 2019), Peak Ground Acceleration (Nurwidyanto et al., 2023), and Ground Shear Strain (Nurwidyanto & Yuliyanto, 2024). These parameters will be a reference for potential building damage and ground deformation during an earthquake in the city of Semarang. Although Semarang is one of the cities with a high seismic risk due to the presence of faults in Semarang, there is no comprehensive microzonation map that covers the entire administrative area of the city with a high density of observation points. Research for the South Semarang area is still very minimal, in addition, the characteristics of the sedimentary layer in the transition area to the hills have not been identified in detail. This research is expected to explain and understand the potential geohazards in the South Semarang area.

2. STUDY AREA

This research was conducted in the southern region of Semarang City, Central Java, Indonesia which is geographically located at $7^{\circ}0'1.47''\text{S}$ & $110^{\circ}23'20.59''\text{E}$ to $7^{\circ}3'15.45''\text{S}$ & $110^{\circ}28'47.93''\text{E}$. **Fig.1** shows the location of the microtremor station area and the presence of faults in Semarang. Thanden (1996) revealed that in Semarang there are several faults located around the research area, namely the Kendang-Baribis fault, the Kaligarang fault, and the Semarang fault. There are 8 earthquakes that have occurred around the research area over the past 50 years. The magnitude of the earthquake has a range of 3.7 - 4.8 mb. The largest earthquake occurred in 1986 located in the western side of the Semarang area. This picture explains the potential seismic hazards that will always be faced by the community in this area.

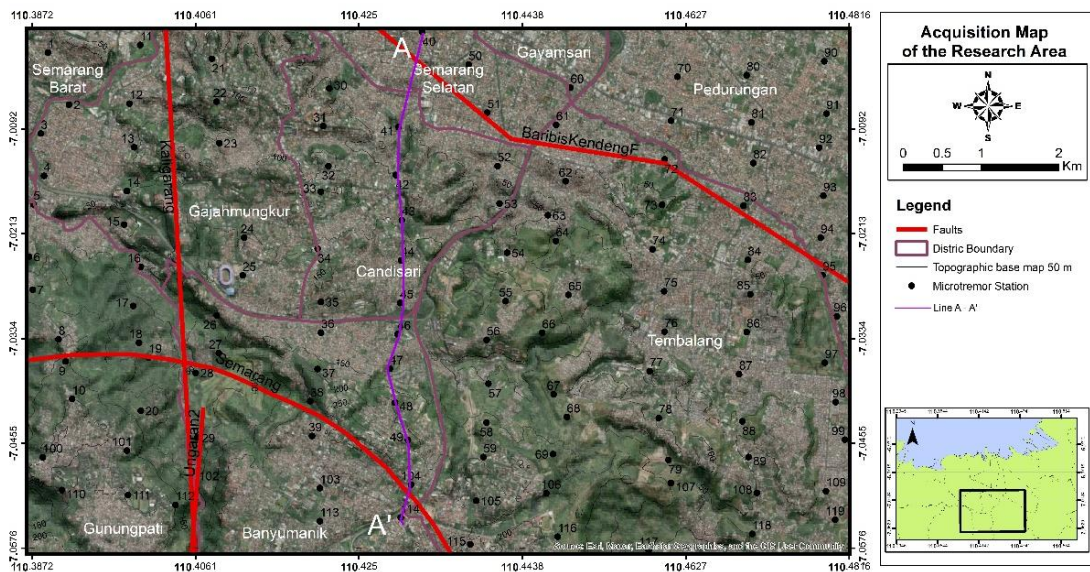


Fig. 1. Map of research location and faults.

Based on the latest data from the BRIN geological expedition (2025), several active fault zones pose a real threat. The Semarang Fault stretches approximately 34 km from north to south. Its characteristics are reverse faults with a potential maximum magnitude of 6.5 to 6.9 Mw (Partono et al., 2020). Traces of these faults are visible in several central points of the city, such as around the Giri Tunggal Heroes' Cemetery (TMP) area, where a fault scarp several meters high was found. The Kaligarang Fault has a path that runs parallel to the flow of the Kaligarang river (Hidayat, 2013). This fault has been active since the Tertiary period and showed reactivity during the Quaternary period as a sinistral strike-slip fault. Poedjoprajitno et al. (2018) noted that the steep morphology around the Kaligarang River, combined with this active fault structure, often triggers slope instability, especially during high rainfall. The National Center for Earthquake Studies (PusGen, 2017) recognized the Kaligarang Fault as part of a fault framework with the potential to produce critical magnitude earthquakes (up to 6.5). The Semarang Fault is part of a larger structure, the Kendeng Fault Zone, which amplifies from West Java to East Java. The section around Semarang-Demak appears clear land elevate.

3. DATA AND METHODS

3.1. Geology of the Research Area

The geological conditions of the research area in Semarang City consist of Alluvial Deposits (Qa), Damar Formation, Kalibeng Formation, Kaligetas Formation, and Kerek Formation. According to Thanden et al. (1996), this alluvial lithology consists of loose sedimentary material in the form of clay, mud, sand, and gravel with varying thicknesses, even reaching more than 50 meters near the coastline (Fig. 2). Alluvial deposits contribute to the high rate of land subsidence in North Semarang, due to the vulnerability of the soil to consolidation due to building loads and excessive groundwater extraction (Abidin et al., 2013). The Damar Formation was formed during the Pleistocene and is of volcanic origin. Its lithology is very diverse, consisting of tuff sandstone, conglomerate, and volcanic breccia that have undergone significant consolidation. Van Bemmelen (1949). The existence of the Damar Formation has a significant impact on the hydrogeology of Semarang City because its sandstone layer functions as a productive aquifer (air-bearing layer). Although in some locations, the slope conditions of this formation are susceptible to landslides. The Kalibeng Formation formed

during the Pliocene and is altered by a lithology consisting of marl, tuff sandstone, and limestone intercalations rich in foraminifera fossils (Thanden et al., 1996). The rocks in this formation tend to undergo rapid weathering and exhibit high swelling and shrinkage, often acting as shear surfaces that cause landslides in several hilly areas of Semarang.

The Kaligetas Formation is a volcanic rock unit formed during the Pleistocene. According to Thanden et al. (1996), this lithology consists of volcanic breccia, lava, tuff, tuff sandstone, and mudstone. The material in this formation is largely derived from the ancient volcanic activity of Mount Ungaran, which subsequently underwent remodeling (Van Bemmelen, 1949). Weathering of this formation produces thick clay residues on steep slopes, often posing a risk of landslides (Sitorus et al., 2017). The Kerek Formation was formed during the Middle to Late Miocene, reflecting an open marine depositional environment (upper bathyal zone). The lithology of this formation is characterized by a very distinctive alternation of mudstone, marl, tuffaceous sandstone, and sandy limestone (Thanden et al., 1996). Van Bemmelen (1949) suggested that the Kerek Formation is part of a thick sedimentary sequence in the North Java geosyncline that experienced strong tectonic deformation, so that its layers are often found in a sharply inclined or folded position.

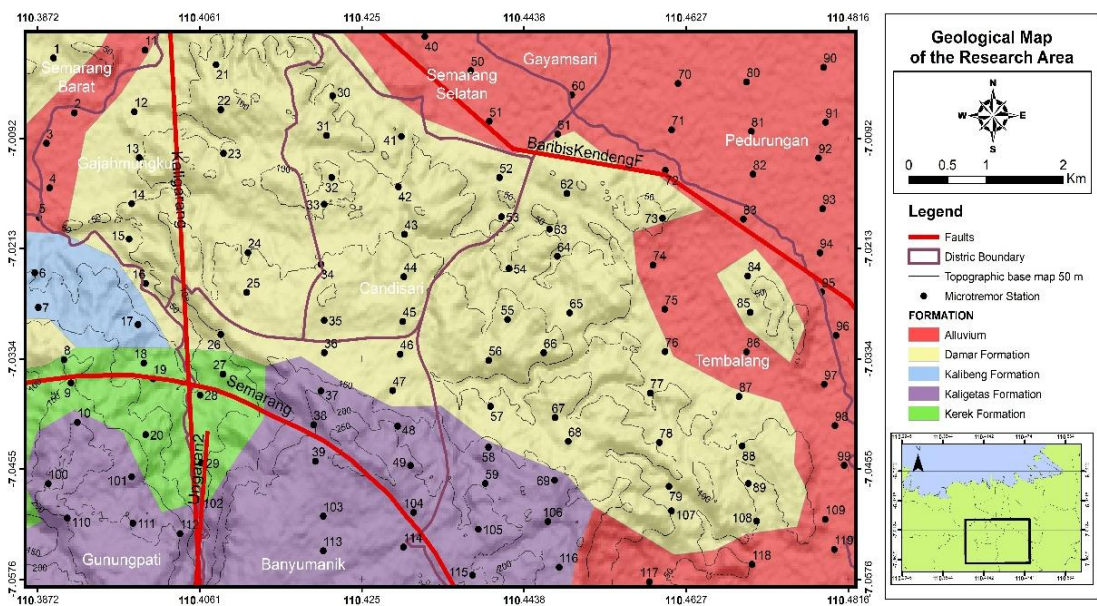


Fig. 2. Geological map of the southern area of Semarang.

3.2. HVSR and Microtremor

Microtremors are exceptionally small natural harmonic vibrations of the ground (micron amplitude) that begin from natural activities such as sea waves and wind, as well as human exercises such as activity and mechanical apparatus. Soil characteristics can be determined by comparing the horizontal and vertical wave spectra of microtremor recordings, commonly known as the Horizontal-to-Vertical Spectral Ratio (HVSR) (Nakamura, 1989). This method is very effective for determining the resonance frequency and intensification factor of an area.

Based on the application, the HVSR method works on the assumption that the vertical component of the microtremor is not essentially amplified when passing through the sedimentary layer, whereas the horizontal component is intensified due to the impedance difference between the soft soil layer and the bedrock. Konno & Ohmachi (1998) emphasize that this spectral ratio can give an outline of the sedimentary layer thickness and the seismic vulnerability of a region. In areas such as Semarang, the use of this method is crucial for mapping the distribution of alluvial layers and identifying zones at risk of severe damage during earthquakes due to local soil amplification effects (SESAME, 2004).

3.2.1. A_0 and f_0

The frequency that frequently occurs in the research area is the dominant frequency and is considered the natural frequency of the rocks in that area. An area experiencing an earthquake or vibration with a frequency similar to the natural frequency will experience resonance, resulting in amplification of seismic waves in that area (Cakici et al., 2021). Buildings with a low dominant structural frequency are therefore susceptible to long-period vibrations and can potentially cause damage due to resonance if the building is constructed in an area with a low dominant frequency (Ilgac et al., 2026). When planning earthquake-resistant building structures, it is necessary to understand the distribution of frequency values in an area to reduce the risk of building damage due to earthquake vibrations (Widodo, 2012). The classification of f_0 values can be found in **Table 1** using the classification of Kanai (1983).

Table 1.

Frequency value classification (Kanai, 1983).

No	Soil Classification Types	Natural Frequency	Description
1	Type 4	< 2.5	The thickness of the surface sediment is very thick
2	Type 3	2.5 – 4	Surface sediment thickness is approximately 10 to 30 m
3	Type 2	4 – 10	Medium surface sediment, thickness around 5 to 10 m
4	Type 1	6.667 - 20	Surface sediments that have a very thin depth

Amplification is the contrast of wave propagation parameters (density and velocity) between the bedrock and the sediment in the overlying layer. Seismic waves will experience amplification if they propagate from a harder medium to a softer medium. This amplification value is closely related to the comparison of the impedance contrast of the rock layers, when the impedance contrast of the two layers is high, the amplification value will also be higher, and vice versa (Nakamura, 2000). The amplification factor explains the change or amplification of the acceleration of ground motion from bedrock to the surface of the soil caused by the difference in shear wave movement speed (v_s) in the bedrock and the soil layer (sediment). The amplification of the acceleration of ground motion on the surface is indicated by the increasing amplification value (Partono et al., 2013). The amplification value can be written as a function of the comparison of the contrast values with the equation (Arifin et al., 2014):

$$A_o = \frac{\rho_b v_b}{\rho_a v_a} \quad (1)$$

where:

- A_0 - Amplification Factor;
- ρ_b - Bedrock density value (g/cm^3);
- v_b - Wave propagation velocity in bedrock (m/s);
- ρ_a - Mass density of soft rock (g/cm^3);
- v_a - Wave propagation speed in soft rock (m/s).

3.2.2. Seismic Vulnerability Index (SVI)

The seismic vulnerability index could be a parameter closely related to the level of vulnerability of a zone to the threat of earthquake risks, the value of which shows a linear relationship with the level of hazard of damage caused by earthquakes. The geological conditions of the local region are a

factor that should be taken into consideration when calculating the value of the seismic vulnerability index of an area (Roser & Gosar, 2010). A thick sedimentary layer accompanied by high amplification will result in a high seismic vulnerability index. The higher the seismic vulnerability index, the greater the potential for structural damage due to weak soil strength. Conversely, a low seismic vulnerability index will reduce the potential for structural damage due to strong soil strength (Hadi et al., 2012).

$$K_g = \frac{A_0^2}{f_0} \quad (2)$$

where:

- K_g - Seismic vulnerability index ($\mu\text{cm}^2/\text{s}$);
- A_0 - Amplification Factor;
- f_0 - Dominant Frequency (Hz).

3.2.3. Peak Ground Acceleration (PGA)

Peak Ground Acceleration is defined as the maximum ground acceleration value that has ever occurred in an area caused by earthquake waves, calculated empirically based on the strength of the earthquake magnitude, the distance of the earthquake source from the measurement point, and the dominant period value of the soil in the area. The resulting maximum ground acceleration value indicates the level of disaster risk that occurs (Nakamura, 1997). According to Douglas (2022), the formulation of the PGA value proposed by Kanai (1996) is that the ground vibration acceleration on the surface becomes maximum with the magnitude of the high wave magnification value, with a period function written in the following equation:

$$\alpha_g = \frac{5}{\sqrt{T_0}} 10^{\left(0,61M - \left(1,66 + \frac{3,66}{R}\right) \log R + 0,167 - \frac{1,88}{R}\right)} \quad (3)$$

where:

- α_g - Peak Ground Acceleration at observation point (gravitational acceleration = gal);
- T_0 - Dominant period of land observation point (s);
- M - Moment Magnitude
- R - Epicenter distance (km)

3.2.4. Ground Shear Strain (GSS)

The ability of soil layers to shift or stretch during an earthquake is called Ground Shear Strain (GSS). The GSS value is obtained by multiplying the PGA and SVI. High levels of vulnerability in an area increase the risk of earthquake-induced ground movement, such as ground cracks, landslides, land subsidence, and liquefaction. The effective value of ground shear strain has an influence on conditions after an earthquake. The potential for deformation, landslides, or liquefaction is shown in **Table 2** (Nakamura, 1997).

Table 2.

Relationship between strain and dynamic properties of soil (Nakamura, 1997).

Size of Strain γ	10^{-6}	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Phenomena	Wave, Vibration		Crack, Settlement		Landslide, Soil Compaction, Liquefaction	
Dynamic Properties	Elasticity		Elasto-Plasticity		Collapse	
					Repeat- Effect, Speed- Effect of Loading	

3.3. Data Collection Method

This study, conducted to determine seismic vulnerability in the upper part of Semarang City, involved recording microtremor signals at 119 locations. The recording equipment used in this study consisted of three sets of microtremor devices, each with a data logger, a VHL PS 2B 3-component seismograph, a GPS, and a compass to determine the North-South direction of the data collection. In addition to the hardware, the software used for data processing in this microtremor (HVSr) method includes Microsoft Excel, Notepad, Notepad++, Geopsy, and Dinver (Irham et al., 2021; Arintalofa et al., 2022). The initial results of the microtremor data recording are raw data, which are obtained in CSV format and can be opened in Microsoft Excel. This data demonstrates the microtremor reaction, revealing a subsurface image with three components (Yulianto & Yuliyanto, 2023): the East-West level component, the North-South horizontal component, and the vertical component (**Fig. 3**). These three components will then be processed using Geopsy software to create an HV curve (**Fig. 4**), which produces A_0 and f_0 values.

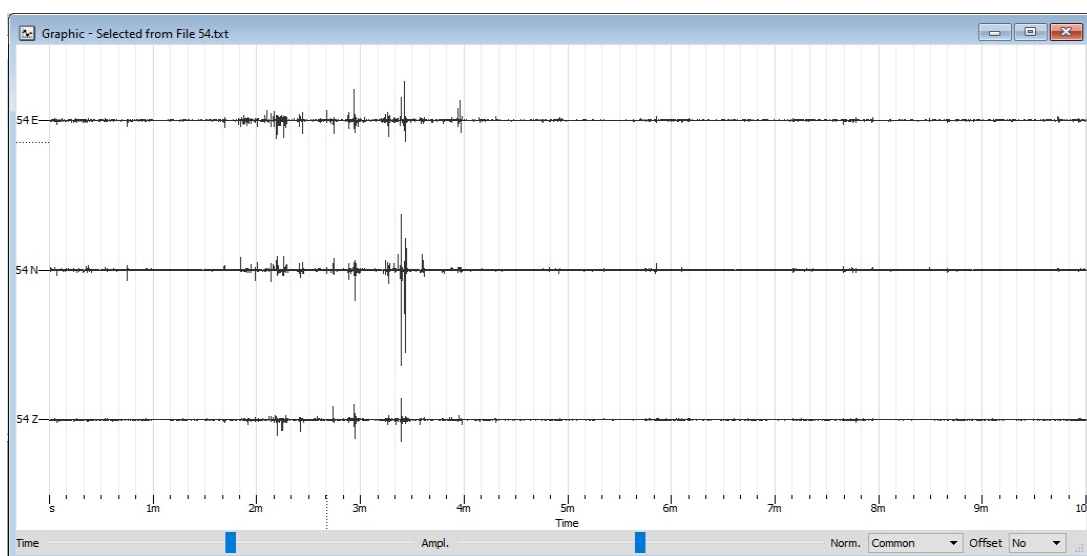


Fig. 3. Microtremor Raw Data.

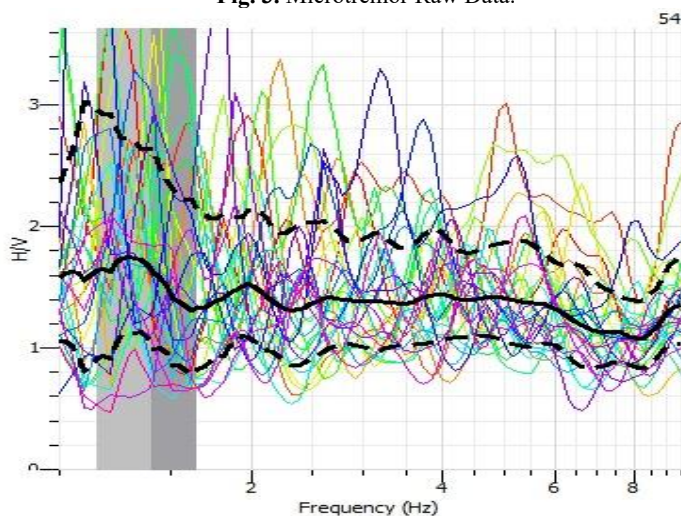


Fig. 4. HVSr processing results.

4. RESULTS

4.1. f_0 (Dominant frequency)

The frequency value of the rock layer in a region can be interpreted as a dominant frequency, which indicates the thickness of the soft layer in that area. Based on the classification explained by Kanai (1983), a higher f_0 value indicates the presence of hard rocks in shallow areas and a thinner surface layer. Meanwhile, greater thickness and softer sediments are associated with smaller dominant frequency values. The southern Semarang area has a dominant frequency value in the range of 0.13 – 9.21 Hz, with an average at 119 station locations of 1.17 Hz, as shown in Fig.5. In general, the research area has a dominant frequency classification of $f_0 < 2.5$ Hz, indicating that most areas are classified as soft soil with a depth of 30 m. Dominant frequencies with a range of $2.5 < f_0 < 6.67$ Hz are found at stations 36, 70, 77, 87, and 118, indicating the presence of soft soil with a thickness of 5 m and consisting of gravelly sand, hard sandy loam, clay, and clay. The f_0 value with a range of $6.667 < f_0 < 20$ Hz is found in the central part of Pedurungan District (station 72), the Southwest part of Pedurungan District (station 72), the northeastern and northern parts of Tembalang District (stations 83, 62), and the southern and western parts of Gajahmungkur District (stations 4 and 15). This classification indicates the presence of a classification of Tertiary or older rocks consisting of hard gravelly sandstone.

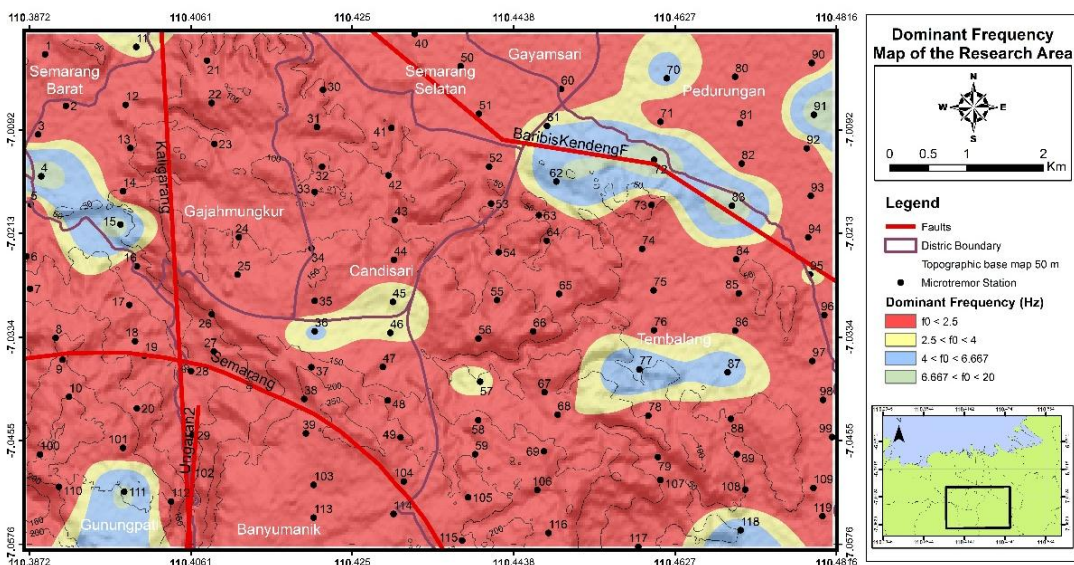


Fig. 5. Dominant frequency map of the research area.

4.2. A_0 (Amplification Factor)

The amplification factor can be defined as a phenomenon where earthquake waves experience an increase in amplitude (shaking strength) as they propagate through certain soil layers, especially soft soil or sediment (Elbsheshi et al., 2022). This occurs because earthquake waves possess energy. When waves move from a hard medium (high propagation velocity) to a soft medium (low propagation velocity), their speed decreases. To maintain constant energy, the amplitude (wave height) must increase drastically. The greater the impedance difference between the bedrock and the surface soil layer, the greater the amplification factor (Farahani & Zare, 2014). The dependent variables in the amplification factor are sediment thickness, lithology, topography, and resonance. The amplification factor (A_0) value in the southern Semarang area ranges from 0.53 to 6.94 with an average of 2.77 (Fig. 6). Based on this, the research area is dominated by amplification classifications

$A_0 < 3$ and $3 < A_0 < 6$. However, in the Northwest part of Tembalang District (station 54), there is a classification of $6 < A_0 < 9$, which is classified as high amplification and requires special attention and handling.

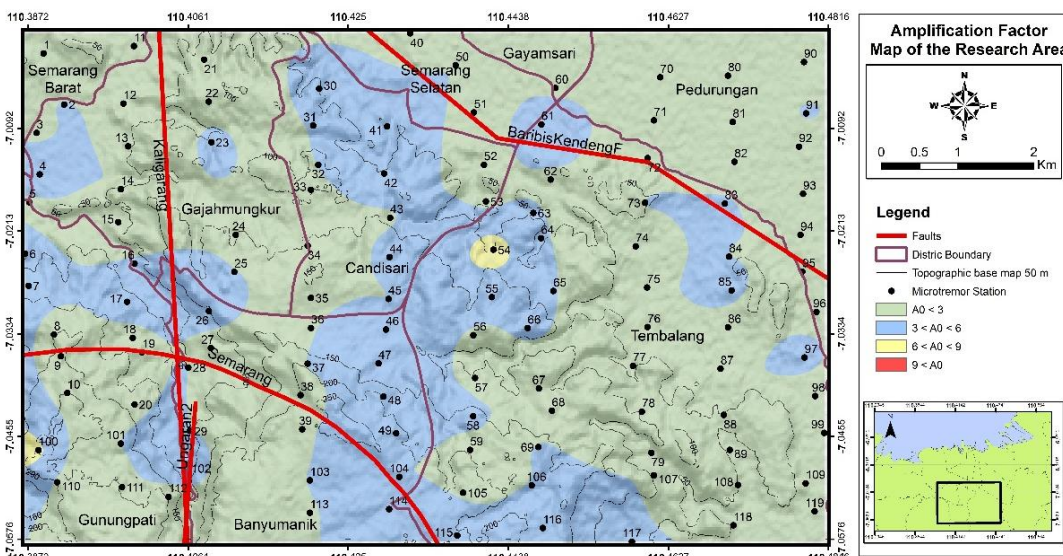


Fig. 6. Amplification Factor Map of the research area.

4.3. SVI (Seismic Vulnerability Index)

The Seismic Vulnerability Index (SVI) can be defined as a numerical parameter used to identify the level of vulnerability of a soil layer to deformation during an earthquake. This index is an important indicator in seismic microzonation studies to map areas most at risk of structural damage due to their geological conditions (Elbshbeshi et al., 2022). The potential impact and hazard of an earthquake increase with the value of the seismic vulnerability index of a region. The thickness of the sediment layer below the ground surface, the surface wave velocity, and the wave velocity below the ground surface are variables used to calculate the seismic vulnerability index value. The Seismic Vulnerability Index value in the southern Semarang region ranges from 0.17 to 260.09 $\mu\text{m}^2/\text{s}$ with an average of 32.29 $\mu\text{m}^2/\text{s}$. Based on Fig. 7, low classification in zone 1 with a range of values $5 \mu\text{m}^2/\text{s} > \text{SVI}$ was found in West Semarang District (station 11), Gajahmungkur District (stations 4, 15, and 24), South Gunungpati District (station 111), South Candisari District (stations 36, 45, 46), North, Central and South Tembalang District (stations 62, 72, 68, 77, 87, 118, 98) and South and Central Pedurungan District (stations 70, 71, 82, 91, 92, 93, 95). Medium classification is in zone 2 with a range of values $5 < \text{SVI} < 25 \mu\text{m}^2/\text{s}$, and high classification, $\text{SVI} > 25 \mu\text{m}^2/\text{s}$ is the dominant classification found in the South Semarang area.

4.4. PGA (Peak Ground Acceleration)

PGA can be defined as the maximum ground vibration acceleration value that occurs at a location during an earthquake. Unlike magnitude, which measures the energy at the epicenter (focal point), PGA measures what is actually felt and experienced by the ground surface at a specific location (Fahrezi et al., 2025). Factors that influence the PGA value are the earthquake source, trajectory, and local conditions. The calculation method in this study uses the PSDA (Deterministic Seismic Hazard Analysis) method, which calculates the worst-case scenario from a specific earthquake source (Kanai, 1996).

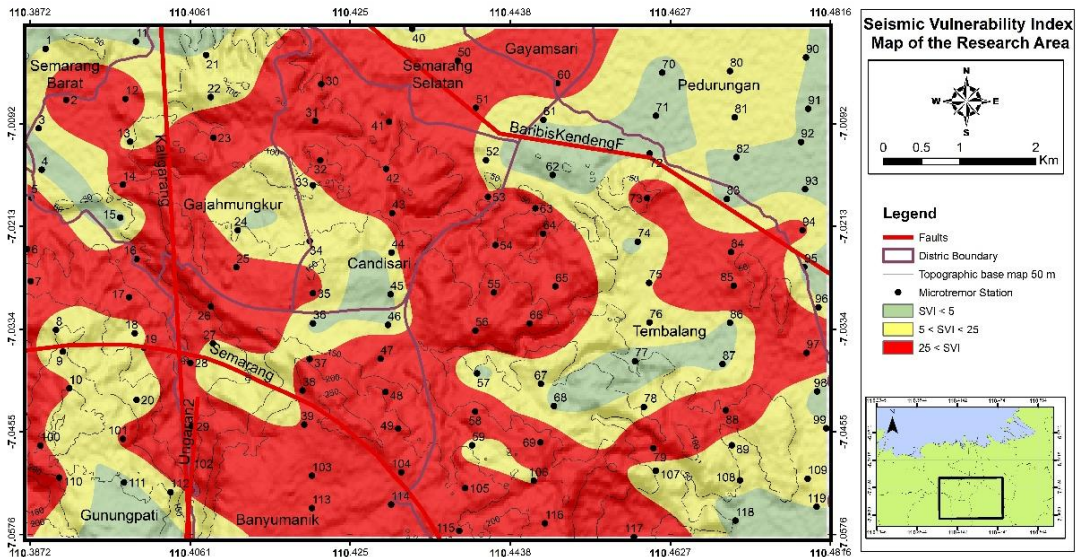


Fig.7 Seismic Vulnerability Index Map of the study area

The earthquake used in this analysis was an earthquake that occurred in Yogyakarta with a magnitude of 6.3. Despite its considerable distance, the presence of a thick and soft alluvial layer in North Semarang causes seismic wave amplification (Partono et al., 2015). This was demonstrated in the 2006 Yogyakarta earthquake (magnitude 6.3), where the tremors were felt quite strongly in Semarang and caused cracks in several building structures, even though the epicenter was hundreds of kilometers from Semarang City.

The presence of active faults that encompass dense organizational and industrial areas can increase the city's seismic risk profile (Azizah et al., 2018), mainly due to the combination of earthquake threats in the environment and soil conditions that are susceptible to land subsidence.

Based on Fig. 8, the PGA value in the southern Semarang area ranges from 5.87 to 49.17 gal with an average of 13.85 gal.

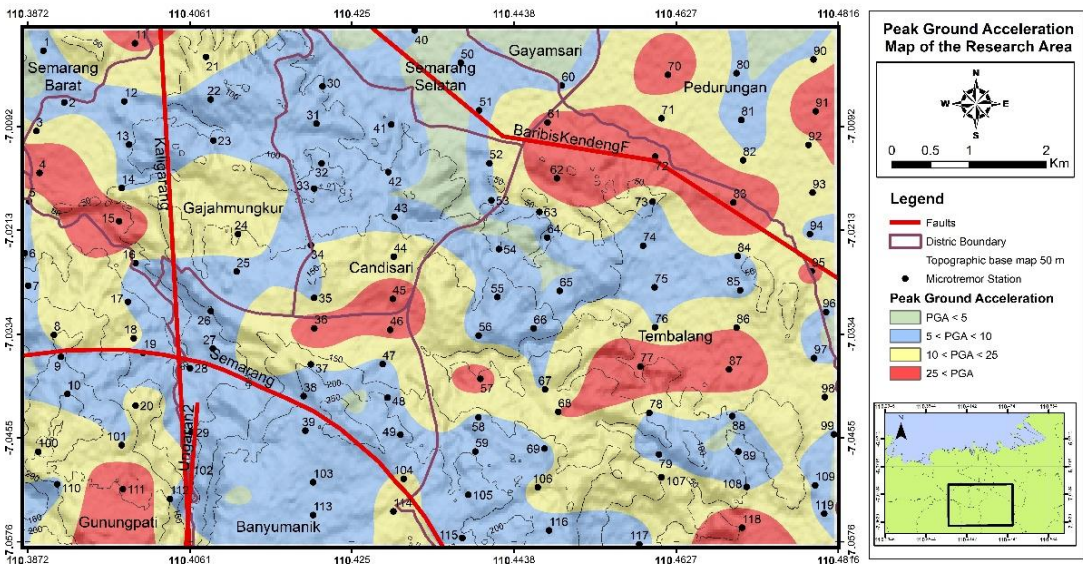


Fig. 8. PGA map of the research area.

The dominant classifications found in the southern Semarang area are $5 < \text{PGA} < 10 \text{ gal}$ and $10 < \text{PGA} < 20 \text{ gal}$, which indicate a moderate area. There are PGA values with high classification, namely in the western part of Gajahmungkur District (stations 4, 15), the southern part of West Semarang District (station 11), the northern part of Banyumanik District (stations 36 and 46), the southern part of Candisari District (station 45), the northern, southern and central districts (stations 61, 62, 72, 83, 57, 77, 87, and 118), the western part of Pedurungan District (stations 70, 91, and 95), the southern part of Gunung District (station 111).

4.5. GSS (Ground Shear Strain)

Ground Shear Strain (GSS) is a critical parameter for assessing the risk level of soil deformation, especially due to dynamic loads such as earthquakes. High GSS values in an area increase the risk of ground movement due to earthquakes, such as ground cracks, landslides, land subsidence, and liquefaction (Nakamura, 1997). The effective value of ground shear strain has an influence on conditions after an earthquake. The classification used in determining the GSS value uses the Nakamura 1997 classification. The GSS value in the southern Semarang area, based on Fig. 9, has a range of $1.3 \times 10^{-5} - 3.59 \times 10^{-4}$ with an average of 1.3×10^{-4} . Most of the southern Semarang area is classified as $1 \times 10^{-4} < \text{GSS} < 1 \times 10^{-3}$, which has the phenomenon of ground cracks and land subsidence, and has elastic-plastic dynamic properties with the effects of repeated loading and speed effects. There is an area with a GSS classification of $< 1 \times 10^{-4}$, namely in the Central Pedurungan area (station 90). This area experiences wave phenomena, vibrations, and has plastic dynamic properties.

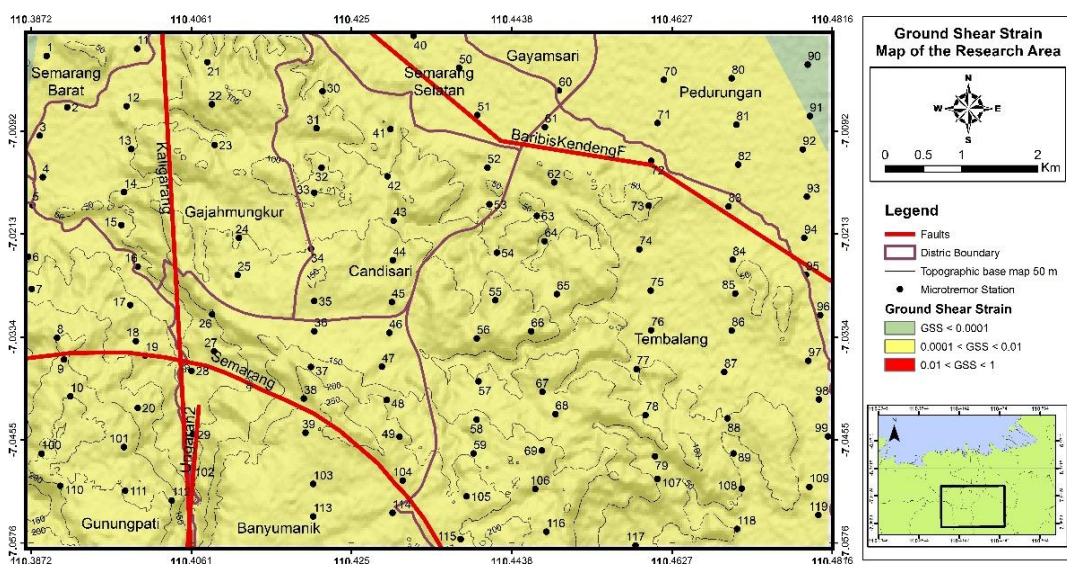


Fig. 9. GSS map of the research area

5. DISCUSSION

Based on the correlation analysis results of the HVSR method (Fig. 9) parameters in the form of dominant frequency (f_0), amplification factor (A_0), seismic vulnerability index (SVI), Peak Ground Acceleration (PGA), and Ground Shear Strain (GSS), a close relationship was obtained in describing the subsurface characteristics and the level of earthquake vulnerability in the southern Semarang region. Line A-A' in Fig. 1 includes several microtremor stations, namely stations 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 104, 114. The dominant frequency (f_0) value in the study area is dominated by a range of less than 2.5 Hz, with an average of 1.17 Hz. This value indicates that most of the area is composed of a soft sediment layer with a relatively large thickness. This condition causes the soil's

ability to respond to seismic waves to be greater, especially in the form of wave amplitude amplification. The f_0 value is closely related to bedrock depth, with low f_0 values indicating deep bedrock and thick sediment layers. Similar research (in the northern region of this study) indicates low f_0 values (Nurwidyanto et al., 2023). This is in line with the distribution of amplification factor (A_0) values in the study area, which are dominated by low to moderate classifications ($A_0 < 3$ and $3 < A_0 < 6$), with several locations showing high amplification values ($A_0 > 6$). The presence of a significant impedance contrast between the bedrock and the overlying sedimentary layer indicates a high amplification factor. The decrease in seismic wave velocity, coupled with constant wave energy, indicates that seismic waves propagate from a hard to a soft medium. Therefore, this correlation indicates that areas with low f_0 values have high A_0 values.

The correlation between f_0 and A_0 is reflected in the seismic vulnerability index (SVI) values (Fig. 9), which show a predominance of high classifications ($SVI > 25 \mu\text{cm}^2/\text{s}$) in most of the study area. A low f_0 value combined with a high A_0 value results in high seismic vulnerability, or susceptibility to earthquake shaking. The SVI value in an area can be used as a reference parameter for seismic vulnerability, as evidenced by research by Nurwidyanto et al. (2024) conducted in the coastal area of Demak. This study showed low SVI values in most of the study areas. These values can also be used as geotechnical recommendations for several areas with high potential seismic vulnerability. The PGA value is influenced by the earthquake source and the distance from the source to the study site. Local conditions such as soil type and sediment thickness also play a role in modifying the acceleration felt at the surface. The Peak Ground Acceleration (PGA) value in the southern Semarang area is classified as moderate to high ground motion. Local soil conditions play a significant role in increasing the intensity of the perceived shaking.

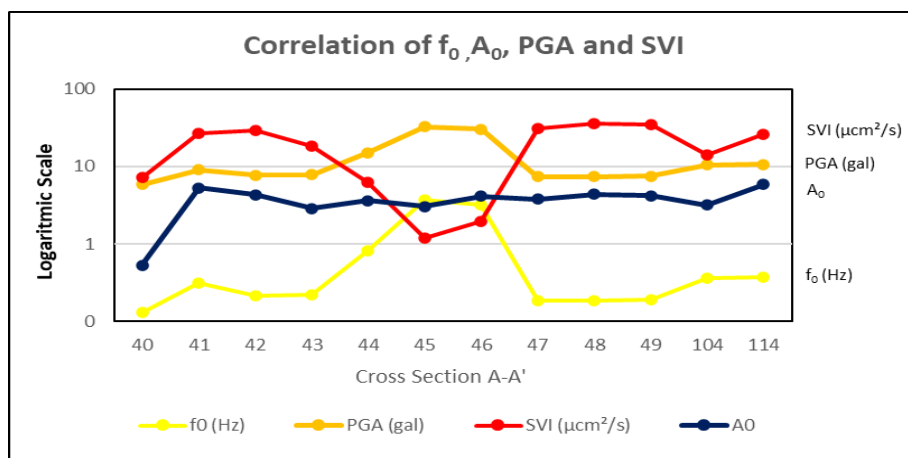


Fig. 9. Correlation between f_0 , A_0 , PGA and SVI in Line A – A'.

The Ground Shear Strain (GSS) value in the study area is in the range of 10^{-4} , which indicates that most areas have the potential for significant deformation. The GSS value indicates the potential for phenomena and dynamic properties experienced by an area. Several previous studies, such as Nurwidyanto et al. (2023), on earthquake microzonation using the HVSr method in the northern area of this study, indicate that most of the northern coast of Semarang is dominated by moderate vulnerability. Meanwhile, several areas across Semarang City, from north to south, have low earthquake vulnerability. These results are based on GSS calculations in various areas.

Therefore, it can be concluded that the GSS value has a positive correlation with SVI and A_0 , and a negative correlation with f_0 . The relationship between parameters shows that the dominant frequency (f_0) is inversely proportional to other vulnerability parameters, while the amplification factor (A_0), seismic vulnerability index (SVI), Peak Ground Acceleration (PGA), and Ground Shear Strain (GSS) are directly proportional. Based on the relationship analysis, it can be concluded that the

southern Semarang region is dominated by geological conditions in the form of soft sediment with a fairly large thickness, which causes the potential for wave amplification and high vulnerability to earthquakes. This condition requires attention in spatial planning and disaster mitigation, especially in areas with high amplification values and vulnerability indexes.

6. CONCLUSIONS

Based on several parameters used to determine seismic hazard potential, the upper part of Semarang City has a relatively high seismic vulnerability index in several areas. Furthermore, spatial analysis also shows that several sub-districts, particularly Tembalang, Banyumanik, and Pedurungan, have a higher earthquake vulnerability than the surrounding areas. These findings provide important information for seismic microzonation, supporting urban planning and information related to disaster mitigation in Semarang City. Furthermore, more in-depth technical studies are needed in the geotechnical field in several locations with high seismic hazards (contained in the A_0 , f_0 , PGA, SVI, and GSS maps), and locations around faults in the Semarang area.

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