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Microtremor Analysis to Identify Fissure Vulnerable Zones in Demak, Central Java, Indonesia

(Analisis Mikrotremor untuk Mengenal Pasti Zon Terdedah Rekahan di Demak, Jawa Tengah, Indonesia)

Rahmadany Leonita[1], Sismanto[1,*], Marjiyono[2]

[1]*Department of Physics, Faculty of Mathematics and Natural Science, Universitas Gadjah Mada, Kaliurang Street Km 3, Yogyakarta, Indonesia*
[2]*Bandung Geological Survey Center, Diponegoro Street No. 57, Bandung 40122, Indonesia*

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ABSTRACT

Demak Regency, located in Central Java, Indonesia stands out among the regencies for its rapid development and regional growth, leading to a significant reliance on groundwater. This is thought to be caused by low precipitation and the geological characteristics of Demak Regency, which is mostly located on alluvial plains. To address these concerns, this study aimed to pinpoint regions vulnerable to ground fractures resulting from excessive groundwater extraction compounded by seismic activity. The research encompassed 191 locations, including 177 single station microtremor measurement points and 14 array microtremor measurement points. Single station microtremor measurements utilized the Horizontal to Vertical Spectral Ratio (HVSR) method, while array measurements employed the Spatial Autocorrelation (SPAC) method. Ground shear strain values spanning from 32.12×10^{-6} - 96.39×10^{-6}. Notably, areas exhibiting heightened values are concentrated in Wonosalam Subdistrict and the Southwest of Karangtengah Subdistrict. The morphology of the bedrock within the study area tends to mirror the sedimentary layer's thickness, reflecting relatively minimal surface height discrepancies at the measurement points. Vulnerability to fissures resulting from excessive groundwater extraction and seismic activity is concentrated on the north side of Wonosalam District, the eastern sector of Demak District, and a small section of Mijen District.

Keywords: Bedrock; Demak; fissures; HVSR; microtremor; SPAC

ABSTRAK

Keregenan Demak yang terletak di Jawa Tengah, Indonesia menyerlah dalam kalangan keregenan kerana pembangunan pesat dan pertumbuhan wilayahnya yang membawa kepada pergantungan yang ketara kepada air bawah tanah. Hal ini disebabkan oleh curahan hujan yang rendah dan ciri geologi Keregenan Demak yang kebanyakannya terletak di dataran aluvium. Untuk menangani kebimbangan ini, kajian ini bertujuan untuk menentukan kawasan yang terdedah kepada keretakan tanah akibat daripada pengekstrakan air bawah tanah yang berlebihan ditambah dengan aktiviti seismik. Penyelidikan itu merangkumi 191 lokasi, termasuk 177 titik pengukuran mikrotremor stesen tunggal dan 14 titik pengukuran mikrotremor tatasusunan. Pengukuran mikrotremor stesen tunggal menggunakan kaedah Nisbah Spektrum Mendatar ke Menegak (HVSR), manakala pengukuran tatasusunan menggunakan kaedah Autokorelasi Spatial (SPAC). Nilai terikan ricih tanah menjangkau daripada 32.12×10^{-6}- 96.39×10^{-6}. Terutamanya, kawasan yang menunjukkan nilai tinggi tertumpu di Mukim Wonosalam dan Barat Daya Mukim Karangtengah. Morfologi batuan dasar dalam kawasan kajian cenderung untuk mencerminkan ketebalan lapisan sedimen, mencerminkan percanggahan ketinggian permukaan yang agak minimum pada titik pengukuran. Kerentanan kepada rekahan akibat daripada pengambilan air bawah tanah yang berlebihan dan aktiviti seismik tertumpu di sebelah utara Daerah Wonosalam, sektor timur Daerah Demak, dan sebahagian kecil Daerah Mijen.

Kata kunci: Batuan dasar; Demak; HVSR; mikrotremor; rekahan; SPAC

Introduction

Ground fissures are cracks in the ground caused by land subsidence. In large cities like Jakarta and Semarang, the primary cause of ground fractures is the lowering of the water table due to excessive groundwater extraction. Ground fissures can be caused by several factors, including low rainfall intensity, long dry seasons, declining water table levels, earthquakes, and significant bedrock elevation differences within a small area. A long dry season can reduce soil moisture, leading to soil shrinkage and cracking. Ground fissures events triggered by geological phenomena such as earthquakes occurred in Cianjur in 2022 (Selamet 2022), while those resulting from tectonic activity in the Linfen Basin, China, in 2020 (Chang et al. 2020). The morphology of the bedrock plays a crucial role in determining the location and geometry of fissures, although the bedrock surface may be hidden by sediments. Figure 1 shows an illustration of soil fissures (Ovando-Shelley et al. 2012).

Demak Regency is one of the regencies in Central Java that has experienced a rapid level of development and regional growth. This growth is evident as Demak and its environs have been integrated into the National Strategic Area (KSN) as outlined in the Presidential Regulation of the Republic of Indonesia (PP RI) Number 60 of 2022, delineating the Spatial Plan of the National Strategic Area of the Kedungsepur Urban Area (Kendal, Demak, Ungaran, Salatiga, Semarang, and Purwodadi). One of the primary aims of this designation is to enhance the functionality of the central urban area and its neighboring regions, serving as a catalyst for socio-economic activities that share functional relationships within the community. The development patterns of regions or cities can be observed through demographic changes and transformations, along with shifts in urban populations. These changes are often influenced by the reclassification of areas previously categorized as rural, subsequently transitioning to urban status at a later point in time (Mardiansjah & Rahayu 2019).

The precipitation in various regions across Indonesia is decreasing by an average of 2% - 3% per year, and this decline is anticipated to intensify during the dry season, potentially resulting in prolonged droughts. This concerning trend is exemplified by the drought disaster that affected 62 villages across 5 sub-districts in 2023 (Utama 2023). In Demak Regency, the drought falls under the category of meteorological drought, characterized by an extended period of comparatively lower rainfall than usual, consequently leading to an extended dry season in Demak Regency. According to the 2011 Demak RTRW (Spatial Planning Document) data, most of the precipitation, standing at 65%, falls within the low category. This statistic highlights a limited water supply derived from rainfall, posing a potential risk of drought. RTRW regulates the spatial arrangement of an area, whether it be at the national, regional, or local level. RTRW aims to manage land use in a planned and directed manner, including the development of infrastructure, settlements, agriculture, industry, and conservation areas. This document is crucial in the development planning process of an area to ensure that the development aligns with existing needs and potentials while being economically, socially, and environmentally sustainable.

Rainfall patterns significantly influence rock properties. Rocks exposed to prolonged dry seasons or droughts are more susceptible to cracking and fracturing, particularly if they have a low rock quality factor (Q factor). This increased susceptibility is because such rocks exhibit high energy absorption. Conversely, rocks that remain intact during extended dry periods are considered to be of higher quality due to their low energy absorption. The rock quality factor (Q factor) is an indicator of a rock's ability to transmit seismic waves. Rocks with low Q factors absorb a substantial amount of energy, weakening seismic waves as they travel through the rock mass. Conversely, rocks with high Q factors effectively transmit seismic waves, allowing them to travel over greater distances with minimal energy loss (Munadi 2000).

Alongside the low precipitation, factories, hotels, and agricultural industries in Demak District are vying for access to clean water sources. If this is done continuously, it may lead to the emergence of vulnerable fissures in Demak Regency and its surrounding areas. To mitigate the risk of fissure vulnerable in Demak Regency, efforts can be directed towards identifying fissure-vulnerable zones through microtremor measurements. Microtremor measurements can be used to determine the geological conditions and the thickness of the surface sediment layer, providing insights into the state of the bedrock surface (the layer beneath the surface sediment layer) in a given area (Marjiyono et al. 2014).

The outcomes of this research are expected to offer information regarding potential areas susceptible to fissure vulnerable. These findings are intended to serve as a reference for planning groundwater utilization, while also providing an overview of the adverse impacts associated with ground fissure resulting from excessive groundwater extraction and seismic activities.

Materials and Methods

This study was conducted in Demak and the surrounding areas of Demak Regency, Central Java, Indonesia. Based on the geological map of the research area in

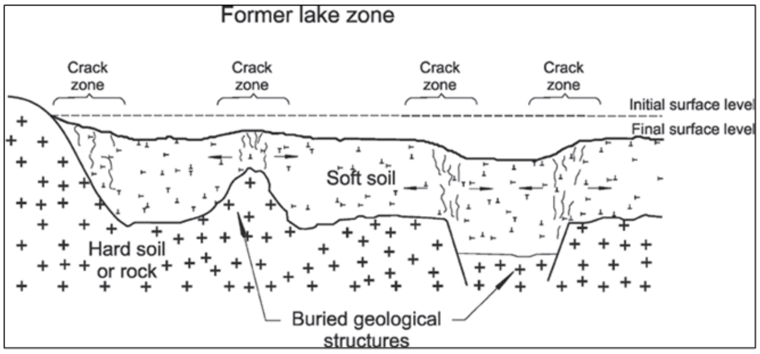


FIGURE 1. Relationship between fissure zones and morphology of bedrock underlying soft layers (Ovando-Shelley et al. 2012)

Figure 2 (modified from Suwarti & Wikarno 1992), the geological conditions of northern Java include a plain of young Holocene alluvium deposits resting on top of the Wonocolo Formation of late Miocene age. These alluvial deposits consist of sand, clay, silt, gravel, as well as remnants of vegetation and volcanic rock fragments. The research area encompasses the sub-districts of Demak, Bonang, Wonosalam, Karangtengah, Gajah, and Guntur. Microtremor data were collected through measurements conducted by the Bandung Geological Survey Center (PSG) team, comprising a total of 14 array microtremor measurement points and 177 single station microtremor measurement points.

The measurement results of single station microtremor data were analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method. The HVSR method is used for analyzing microtremor data by comparing the horizontal spectrum with the vertical spectrum of surface vibration in the frequency domain to determine its geological characteristics. This can be mathematically expressed in Equation (1):

$$HVSR = \frac{\sqrt{\frac{S_{N-S}^2 + S_{E-W}^2}{2}}}{S_{U-D}} \tag{1}$$

where $HVSR$ is the ratio of horizontal and vertical spectrum; S_{N-S} is the amplitude of the frequency spectrum of the north-south component; S_{E-W} is the amplitude of the frequency spectrum of the east-west component; and S_{U-D} is the amplitude of the vertical up-down component frequency spectrum.

The research procedure can be seen in the flowchart (Figure 3(a)). Processing single-station data with the HVSR method in Geopsy software begins with accessing three-component microtremor data in the time domain. The microtremor data obtained from the Geological Survey Center (PSG) is already in the miniseed (.mseed) format, so the first step involves directly importing it into Geopsy. The software then displays the data in the raw data view, as shown in Figure 3(b). Furthermore, the general settings of the data processing (Table 1) to be used in this data processing involve adjusting the Window Length, Smoothing type, Smoothing constant (bandwidth), and Tapering.

Through the analysis of the HVSR method, the amplification value (A) is determined from the peak value of the HVSR curve, and the dominant frequency (f_0) is the frequency value located at the peak of the HVSR curve. Details of the results shown in Figure 3(c) for signal recording A006, as well as for f_0 and A, will be presented in the discussion. Frequency and amplification are parameters that characterize the dynamics of the surface sediment layer. Amplification is the magnification of seismic waves that occurs due to significant differences between layers. In other words, seismic waves experience magnification when they propagate from one medium to another that is softer than the initial medium through which they pass.

The results of the dominant frequency and amplification are subsequently employed to compute the sediment layer thickness, seismic susceptibility index, and ground shear strain (GSS). The seismic susceptibility index (K_g) serves to determine the degree of susceptibility of the surface soil layer to deformation during an earthquake. In thick sedimentary layers with substantial wave amplification, a high susceptibility index is generated. The higher the seismic susceptibility index in an area, the greater the potential damage that may occur in the event of an earthquake (Daryono 2011a). The seismic susceptibility index equation according to Nakamura (2000) can be expressed as follows:

$$K_g = \frac{A^2}{f_0} \tag{2}$$

Nakamura (1989) defines ground shear strain (GSS) as the maximum strain experienced by the surface soil during an earthquake. The GSS value is represented in Equation (3):

$$\gamma = K_g \times 10^{-6} \times \alpha \tag{3}$$

where γ is ground shear strain value and α is PGA value formulated an empirical equation for calculating PGA in the subsurface sediment layer by Fukushima and Tanaka (1990).

The array microtremor data were analyzed using the Spatial Autocorrelation (SPAC) method. The SPAC method is a microtremor measurement technique designed to produce dispersion curves (phase-frequency velocity curves) and model the subsurface secondary wave velocity (Vs) structure within the Earth (Thein et al. 2015). Dispersion is a term that describes the change of phase velocity with frequency (Khalil et al. 2017). This method is employed to ascertain the subsurface velocity profile through the cross-correlation of microtremor recordings.

Sediment thickness is associated with the dominant frequency, which represents the resonant frequency of the surface sediment layer when it reaches its maximum amplification value. The relationship between sediment layer thickness and dominant frequency is described in the equation (Seht & Wohlenberg 1999):

$$f_0 = \frac{V_S}{4H} \tag{4}$$

After obtaining the values of the seismic vulnerability index parameters, peak ground acceleration, ground shear strain, and bedrock elevation, a fissure vulnerable map is created using the Simple Additive Weight (SAW) method. The SAW method is one of the techniques employed to address multi-criteria or multi-attribute decision-making (MADM) problems. Multicriteria decision analysis is a decision-making analysis that involves the evaluation, prioritization, and selection of criteria (attributes) from various alternatives (Azar 2000).

The SAW method is rooted in the concept of average weighting. The total score for the decision is calculated by multiplying the alternative score for each attribute by the attribute weight value and then summing up the multiplication results of all existing attributes. This calculation can be represented by an Equation (5) (Setiawan 2009).

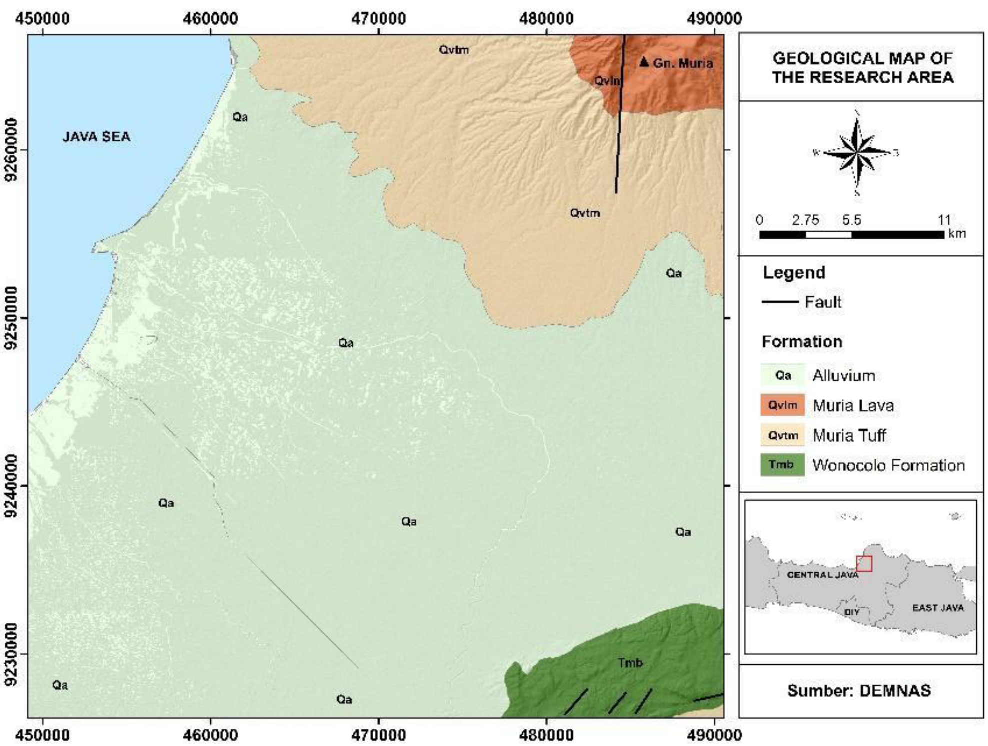


FIGURE 2. Geological Map of Research Area (Modification from Suwarti & Wikarno 1992)

$$A_j = \sum_{j=1}^{n} w_j x_{ij} \tag{5}$$

The weighting is carried out by considering the parameters that exert the most influence on the occurrence of soil fissures. The determination of parameter values and the weight assigned to each parameter is presented in Table 2. The process of creating a map of areas prone to ground cracks due to earthquakes involves several stages:

1. Attribute and attribute weight values determination begins by assigning a value of 1 to the attribute considered least influential, then incrementally increasing the value until it reaches 10 for the most important and influential attribute

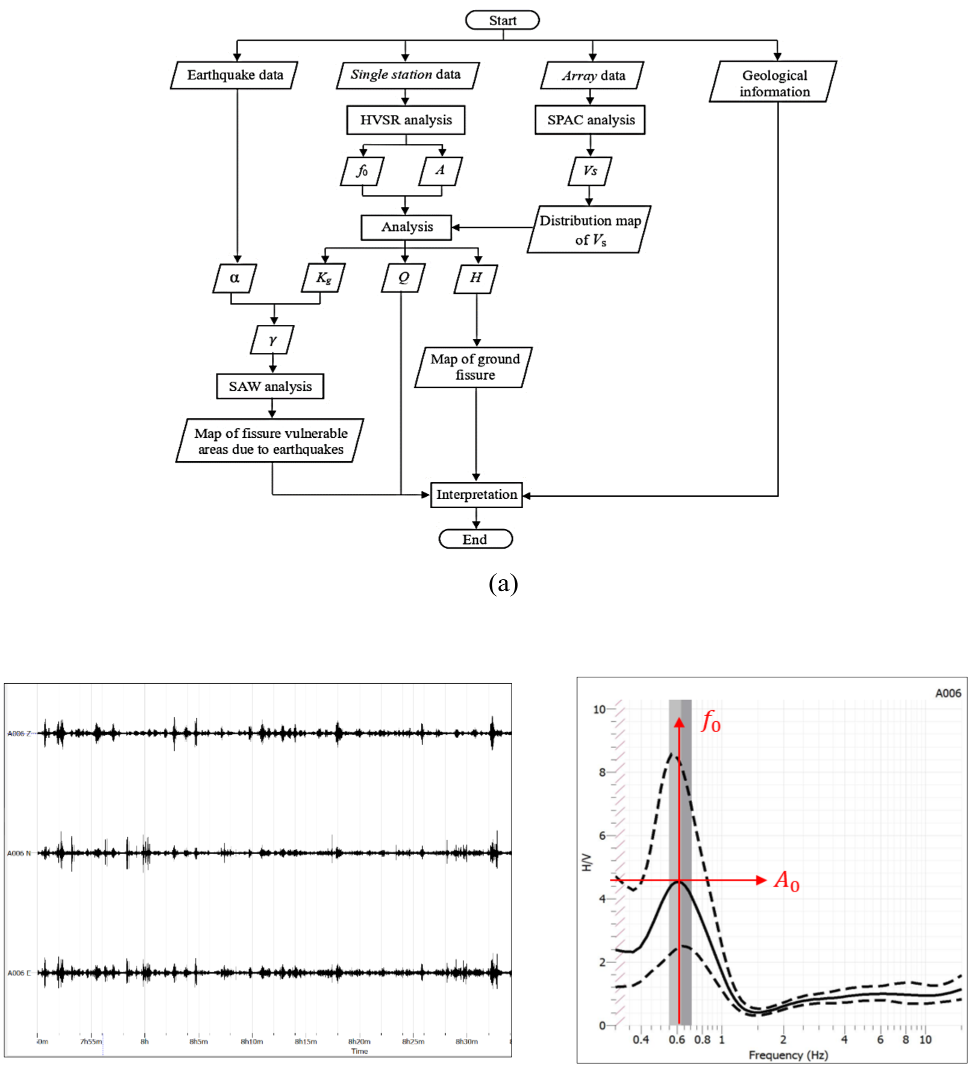
2. Alternative determination for each attribute is carried out as follows: slope classification based on Van Zuidam (1983), amplification factor value attributes grouped into four categories—low, medium, high, and very high (Ratdomopurbo 2008), and earthquake hazard levels grouped into three classes—low, medium, and high based on Head of BNPB Regulation Number 2 (2012)

3. Ranking of each alternative attribute is determined by assigning a value of 1 to the least important or influential attribute and sequentially increasing the value until it reaches 5 for the most important and influential attribute

4. Normalized weights and standardized alternative ranking values for each attribute are calculated

5. Using ArcGIS software, a map is created for each attribute

6. Overall attribute scores are aggregated to generate a map depicting areas prone to ground cracks due to earthquakes



(a)

(b)

(c)

FIGURE 3. 3-components single station microtemor raw data for signal recording A006 (a) and HVSR processing curve (b)

TABLE 1. General setting of microtremor processing

Parameter	Value
Window length	30 s
Smoothing type	Konno & Ohmachi
Smoothing constant (Bandwidth)	15
Tapering type	Cosine Taper
Width	5%

TABLE 2. Weight normalization value and standardization of alternative ranking value of attributes on the map of fissure-vulnerable zones due to earthquakes

Attribute	Weight value (Normalization)	Alternative	Ranking
Slope of bedrock elevation	0,34615	> 40	1
		25 - 40	0.8
		15 - 25	0.6
		2 - 15	0.4
		0 - 2	0.2
Ground shear strain	0,19231	> 64	1
		32 - 64	0.6
		< 32	0.2
Amplification	0,30769	> 9	1
		6 - 9	0.8
		3 - 6	0.6
		< 3	0.4
Peak ground acceleration	0,15385	> 0,70	1
		0,2501 - 0,70	0.6
		< 0,2501	0.2

Results and Discussion

In this study area, most of the H/V curves show a double peak of 113 points and 4 points with clear peak curves out of a total of 191 points. This type of spectrum with a double peak is typically observed in regions with subsurface conditions comprising two sedimentary layers that have a noticeable impedance contrast (SESAME 2004).

The dominant frequency values generated in this study, ranging from 0.39 - 0.90 Hz. Conversely (Figure 4(a)), the dominant frequency tends to be lower in the northwest, particularly in parts of Bonang and Sayung sub-districts, which are near the coast. The dominant frequency values reflect the increasing thickness of the surface sediment layer as one moves towards the coast.

The amplification values obtained from 191 points in this study range from 1.05 - 1.49 (Figure 4(b)). High amplification values are concentrated in the central part of the study area, specifically in the northeast and east, encompassing parts of Mijen Subdistrict, Demak Subdistrict, the northern portion of Wonosalam Subdistrict, and Gajah Subdistrict. The higher the amplification value, the greater the risk of damage. Furthermore, the dominant frequency and amplification values will be utilized to determine the seismic vulnerability index.

The range of seismic vulnerability index values varies from 1.48 - 4.20 (Figure 4(c)). The highest seismic vulnerability index values are situated in the central part of the study area, as well as in the northeast of Mijen sub-district, part of Wonosalam sub-district, and a small section of Bonang sub-district. These elevated seismic vulnerability index values are attributed to the geological composition of the area, which primarily consists of soft alluvium containing gravel, sand, silt, and clay, along with deposits from rivers, lakes, and beaches. The distribution of high K_g values corresponds to areas that experience ground fissures during earthquakes (Daryono 2011b). On the other hand, the research area with a low seismic vulnerability index value is in the northwest, specifically in Sayung sub-district. This area exhibits a low seismic vulnerability index due to its limited amplification value.

In the peak ground acceleration (PGA) calculation, the earthquake source utilized was the earthquake that took place in Bantul, Yogyakarta, on May 27, 2006, with a magnitude of 6.3. The resulting PGA values ranged from 20.02 to 25.88 gal (Figure 4(d)), with PGA values decreasing as the distance from the hypocenter increases. This decrease occurs because the PGA value in bedrock is primarily influenced by the earthquake's magnitude and the distance from the hypocenter. The results of this PGA value calculation will be employed to determine the ground shear strain (GSS) value.

The results of the calculation for ground shear strain (GSS) values at 191 measurement points, ranging from $32.12 \times 10^{-6} – 96.39 \times 10^{-6}$ (Figure 5(a)). The areas with the highest GSS values are situated on the southern side of Wonosalam Subdistrict and the southwest of Mranggen Subdistrict, whereas the lowest GSS values are found in the eastern and western parts of the study area. A high GSS value indicates that the area has unstable soil conditions, making it more susceptible to deformation.

The SPAC measurement values of secondary wave velocity (*Vs*) varied from 81.03 - 113.03 m/s (Figure 5(b)). All secondary wave velocity (*Vs*) profiles show a slight difference in value between the sediment layer and the bed. This indicates that the surface sediment layer and the bottom layer are still of the same lithology. Physically, such a large shear wave velocity value indicates the characteristics of a very soft material. Layers overlying surface deposits with shear wave velocities of around 200 m/s are also classified as soft deposits. Data from geological drilling in the area of Sayung Subdistrict and Mranggen Subdistrict (ESDM 2020) show that up to a depth of 200 m, the layer is interpreted as alluvial deposits. Based on these data, the layer overlying the soft deposits at this surface is thought to be an older part of the alluvial deposits in the Demak area.

The northern part of the study area exhibits lower *Vs* values than the southern part, while the secondary wave speed increases in the eastern region of the study area. This phenomenon is attributed to the proximity to the sea, where the material becomes softer, resulting in smaller secondary wave velocities. The secondary wave velocity (*Vs*) value is subsequently employed to determine the sediment layer's thickness.

The results of the calculation of sediment layer thickness ranges from 21.58 - 66.68 m (Figure 5(c)). The lower distribution is observed in the eastern and central parts of the study area, while it increases as one moves closer to the sea. Additionally, the thickness of the sediment layer is employed to establish the morphology of the bedrock in the study area by subtracting the elevation at the measurement point from the thickness of the sediment layer. The resulting values are subsequently interpolated to provide an overview of the bedrock's morphology, as shown in Figure 5(d).

The f_0 value is linked to the depth of the bedrock, with lower f_0 values signifying the presence of deeper bedrock. As indicated by the bedrock morphology illustration, it is evident that the study area exhibits relatively minor elevation disparities since it is situated in a low-lying region. It can be observed that the bedrock elevation tends to decrease as it approaches the northern coast of the area. The morphology of the bedrock dictates the thickness of the sediment layer.

Additionally, the identification of areas vulnerable to fissures depends on the bedrock's slope in the study area (Figure 6(a)). The steeper the bedrock slope, the greater the potential for soil fissures. The northern part of the research area, particularly in Bonang Sub-district, is situated within a steep basin structure (depicted in red) with a slope ranging between 45 - 47 degrees. This condition renders this area highly susceptible to soil fissures, primarily due to excessive groundwater extraction. This finding aligns with the research conducted by Salsabil et al. (2021), which states that the regions experiencing the most significant declines in groundwater levels are Morodemak, Jatigoro, Serangan, and Wedung Villages in Bonang Subdistrict, each of which exhibits a groundwater level decrease of approximately 10 cm per year. Norhayati et al. (2020) in Ismail et al. (2022) state that groundwater is an alternative source of water that can be found beneath the ground surface, located in cracks or the dissolution zone, as well as in the cavities between sedimentary rock grains.

Furthermore, the identification of earthquake-prone areas vulnerable to fissures is conducted using one of the weighting methods, namely the Simple Additive Weight (SAW) method. Within the SAW method, the following data are employed, each with its respective weight: bedrock slope, amplification, peak ground acceleration, and ground shear strain.

Based on the earthquake-induced fissures vulnerability map depicted in Figure 6(b), the areas with the potential to experience earthquake-induced fissures exhibit a similar pattern to the vulnerability map for groundwater extraction-induced fissures, especially in high-risk regions. This similarity is attributed to the consideration that the bedrock slope and seismic vulnerability index parameters hold more significance in influencing ground fissures compared to the ground shear strain and peak ground acceleration parameters. In the northern part of Demak and Mijen sub-districts, which were previously not prone to fracturing and featured

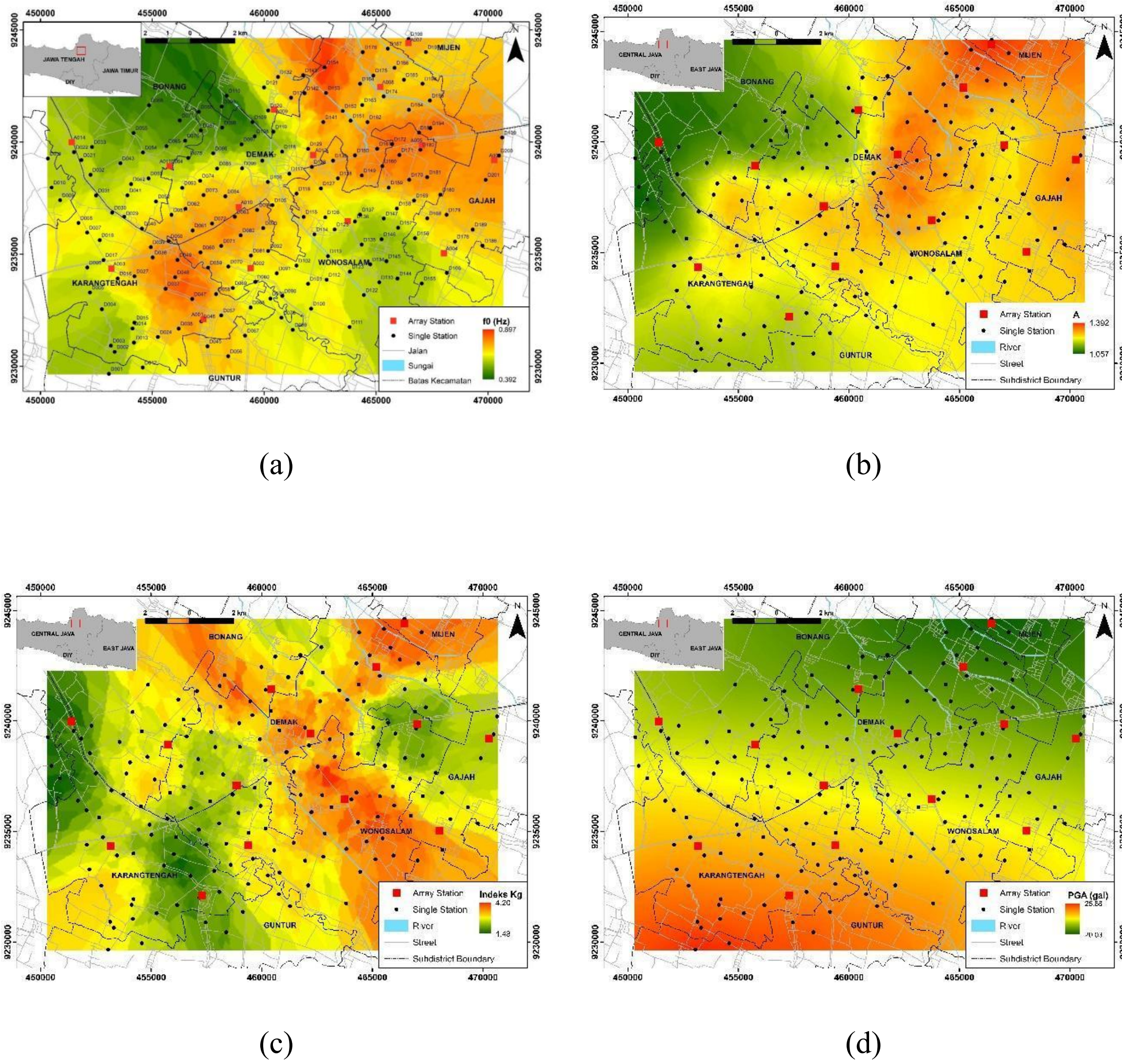
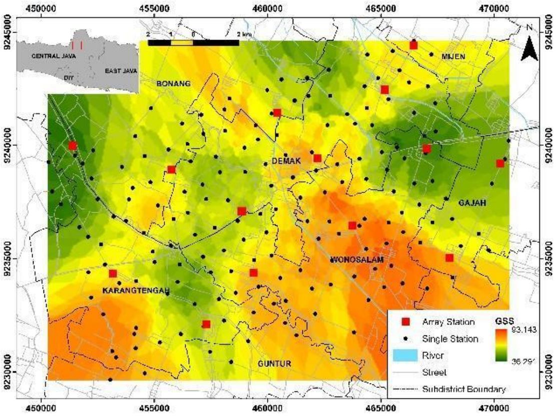


FIGURE 4. Distribution map of dominant frequency (a), amplification (b), seismic vulnerability index (c), and peak ground acceleration (d)

low values of ground shear strain and peak ground acceleration, now fall into a high vulnerability category due to the slope pattern of the bedrock morphology in the area. The presence of this level of vulnerability underscores the potential damage that may occur when the area is subjected to an earthquake.

Areas with high vulnerability are located in the northern part of Wonosalam District, the eastern part of Demak District, and a small part of Mijen District. Areas with medium vulnerability are in almost the entire research area, and low vulnerability areas are located in the northern part of Karangtengah District. Figure 7(b) shows a map of areas vulnerable to fissures. The bedrock layer in the research area is an alluvial deposit consisting of sand, clay, silt, gravel, as well as plant remains and chunks of volcanic rock which are susceptible to movement or compaction during an earthquake.

Additionally, Figure 7(a) and Figure 7(b) depict cross section A-B and cross section C-D, respectively, which illustrate the relationship between the fissures vulnerable zone, groundwater, and the bedrock morphology underlying the surface sediment layer. Bedrock with a steep slope significantly affects the formation of ground fissures. Besides being triggered by earthquakes, ground fracturing is also influenced by the low precipitation and resulting droughts that are prevalent in Demak and its surrounding areas. This is evidenced by the drought that affected 62 villages across 5 sub-districts in 2023 (Utama 2023). The droughts experienced in Demak Regency are classified as meteorological droughts, characterized by longer periods with significantly less precipitation than usual, leading to extended dry seasons. Consequently, low precipitation can be a primary trigger for the formation of ground fractures, altering the landscape's geological structure and character.



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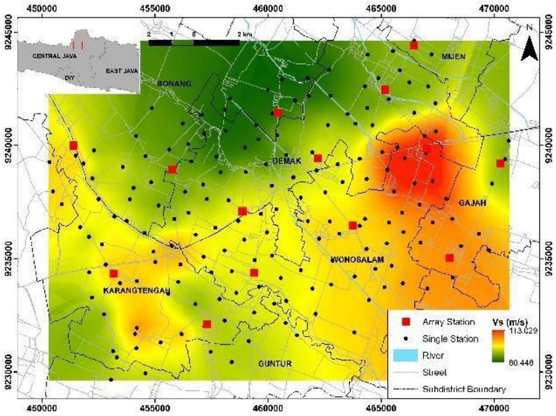

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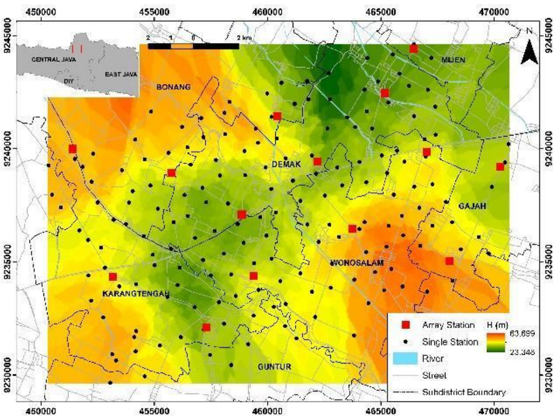

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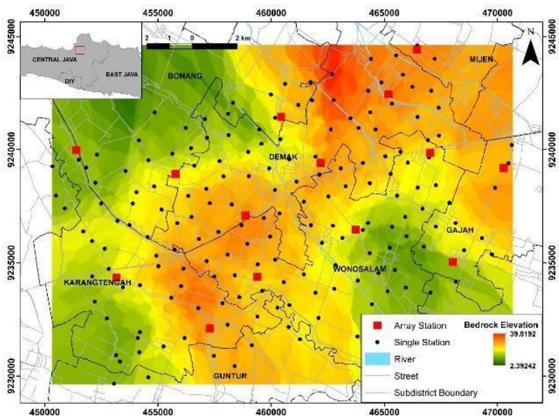
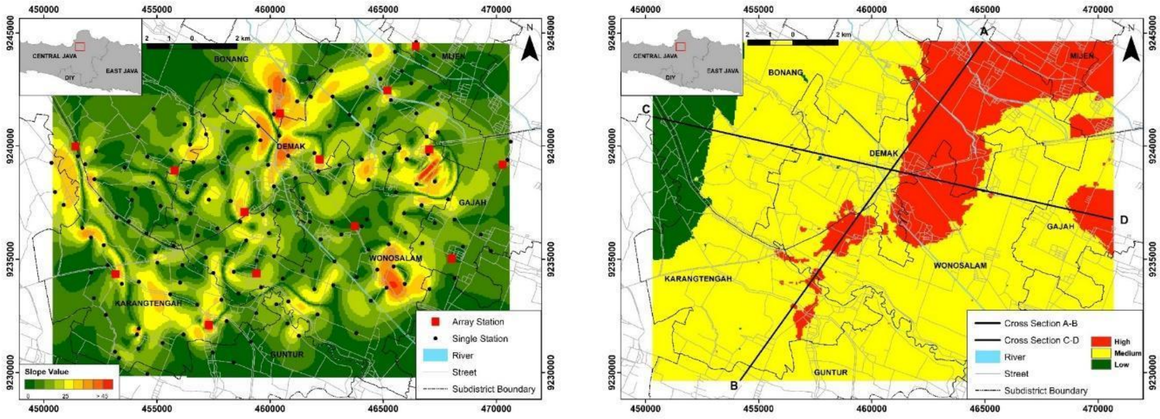


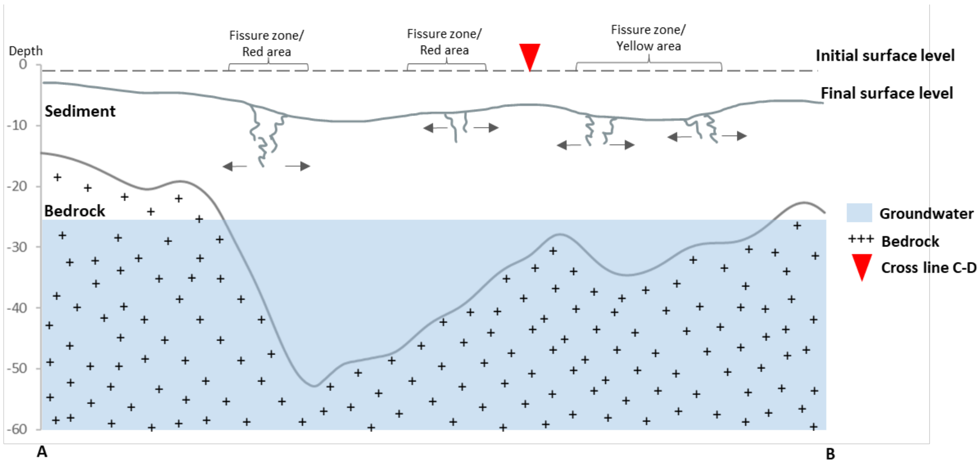
(d)

FIGURE 5. Distribution map of ground shear strain (a), secondary wave velocity (*Vs*) (b), sediment layer thickness (c), and bedrock's morphology (d)



(a) (b)

FIGURE 6. Map of bedrock surface slope (a) and fissure vulnerable areas due to earthquakes based on compilation with SAW method (b)



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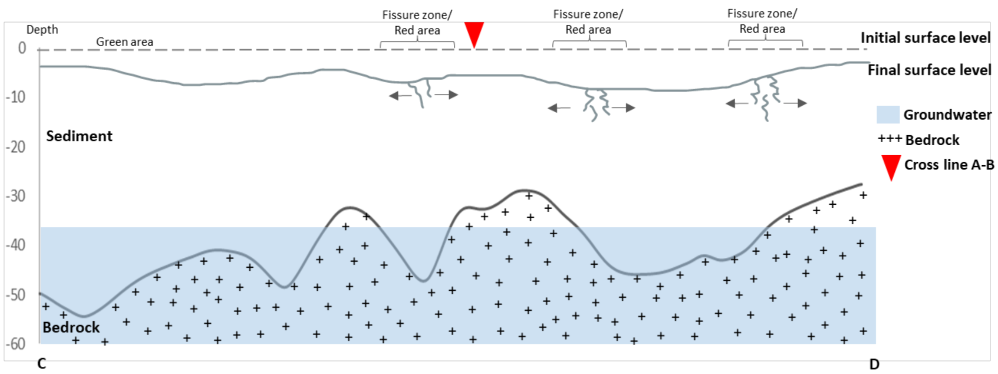

(b)

FIGURE 7. Relationship between fissure zone and bedrock morphology underlying the surface sediment layer in cross section A-B (a) and cross section C-D (b)

CONCLUSIONS

Demak District, Central Java, experiences rapid development and regional growth. This rapid expansion increases the likelihood of Demak becoming susceptible to ground fissures due to a combination of factors: excessive groundwater extraction, frequent earthquakes, and low precipitation. The study of fissure vulnerable zones in Demak District shows that the highest vulnerability to ground fissures lies in the northeastern part, particularly Demak Sub-district and portions of Wonosalam and Mijen. Excessive groundwater extraction and earthquakes are identified as the primary contributors to this heightened vulnerability. This study aims to serve as a valuable reference for future groundwater utilization planning and raise awareness of the potential negative impacts of ground fissures resulting from excessive groundwater extraction and seismic activity.

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*Corresponding author; email: sismanto@ugm.ac.id