MICROZONATION FOR EARTHQUAKE HAZARDS WITH HVSR MICROTREMOR METHOD IN THE COASTAL AREAS OF SEMARANG, INDONESIA

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ABSTRACT:

Semarang coastal area is mainly composed of alluvium sediment, vulnerable to tidal floods caused by land subsidence and seawater inundation. On the other hand, this capital area is also prone to earthquakes evoked by Kaligarang, Semarang, Ungaran 1, and Ungaran 2 Faults. This research aims to examine the earthquake vulnerability index in the coastal area of Semarang using the HVSR (horizontal to vertical spectral ratio) micro tremor method. The study was conducted by measuring the micro tremor signal as many as 110 points spread over the research location with an almost even distribution. Data collection was carried out around existing roads with a distance of about 1000 m west-east and about 500 m north-south. Data was taken with a 3-component TDS seismograph type 303S with a sampling rate of 20 Hz for 10 minutes. The micro tremor data was processed using Software Excel, Pro, and Geopsy data to obtain the dominant frequency values, amplification factor, seismic vulnerability index, Peak Ground Acceleration, and Ground stress-strain. The data obtained is described as a distribution map along with the parameter values using ArcGIS software. The results show that the frequency dominant, amplification, SVI, PGA and GSS vary from 0.13 Hz to 8.44 Hz, from 0.08 to 7.92, from 0.04 gal to 75.74 gal, from 5.75 μs^2/cm to 45.22 μs^2/cm, and from 12.3×10^{-6} – 788×10^{-6}, respectively. The results obtained in the research area that have a vulnerability to earthquakes can be grouped into 3 categories, namely weak, medium and strong categories. Most of the research areas have a vulnerability index to moderate earthquakes, except for the northern and southern parts of West Semarang District, Sayung District, and Genuk District which is in the strong category. Areas with a weak category were found around the eastern part of North Semarang District and Central Semarang District in the northern part, Candisari District, Gayamsari District in the southern part, and Pedurungan District in the southern part. This study was conducted during the rainy season. Therefore, collecting the same data for different season I recommended for further study to investigate the influence of seasonal effects on earthquake-impacted areas.

Key-words*: Micro zonation, Earthquake, SVI, Semarang Coastal, HVSR*

1. INTRODUCTION

Geographical Location Semarang City is located on the north coast of Central Java, precisely at 6º 50″ – 7º 10″ south latitude and 109º 50″ – 110º 35″ east longitude, with an area of about 373.7 km². Semarang is the capital of the province of Central Java and is a fairly densely populated city, some of which are located on the coast. Semarang is bordered by the Java Sea in the north, Demak Regency in the east, Semarang Regency in the south, and Kendal Regency in the west (BPS Semarang, 2022). The coastal area in the northern part of Semarang City is a coastal alluvial plain that extends from east to west and the topography ranges from 1 to 5 m high above sea level.

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The alluvial plain is influenced by coastal and river deposits. In the southern part of Semarang City, there are many hills where volcanic breccia spreads from north to south. These rocks are the result of the eruption of Mount Ungaran, the highest area of Semarang city. The hills of the city of Semarang have a slope of 2% to 40 % and a height of 90 m to 200 m above sea level (Marsudi, 2000). Several active faults have been identified in the Semarang area, such as the Semarang, Kaligarang, Ungaran 1, and Ungaran 2 (Pusgen, 2017). Furthermore, another study defined that the northern and southern of Semarang are separated by the Semarang fault (Hidayat et al., 2014). Several active faults have been identified quite well in the Semarang area, such as the Semarang Fault, Kaligarang Fault Ungaran 1 and Ungaran 2 Faults (Pusgen, 2017). Several studies explain that the fault that divides hight Semarang and low Semarang is known as the Semarang Fault (Hidayat, et al., 2014). The Semarang fault can be recognized from the morphological appearance of the rising fault escarpment that penetrates the Holocene rock (Poedjoprajitno, et al., 2008). The geological structure of Semarang City consists of three parts, namely the joint structure, faults and folds. The fault area is very erosive, has high porosity, and the structure of rock formations is discontinuous and heterogeneous, making it easier for soil migration or landslides.

Geologically, the coastal area of Semarang, Indonesia mainly consist of the alluvium (Qa) deposits which are are quarter old, and only a small part is composed by Damar Formation rocks at the southern part. Alluvium deposits (Qa) are composed of alluvium deposits of beaches, rivers and lakes as shown in **figure 1**. The lithological deposits on the coast consist of clay, silt, sand and a mixture with a thickness of 50 m or more. River and lake deposits consist of gravel, gravel, sand and silt 1 to 3 m thick. The boulders are composed of andesite, claystone and a little sandstone. The Damar Formation of Late Pliocene to Early Pleistocene age is composed of tuffaceous sandstone, conglomerate, volcanic breccia and tuff. Sandstone consists of feldspar minerals and mafic minerals, some tuffaceous and locally there is limestone. As for breccias, the fragments are generally alkaline volcanic rocks and outcrops found in Kedung Mundu, Karanganyar, and Ngadirejo (Poedjoprajitno, et al., 2008). Semarang has active seismic activity, so the Semarang area is likely to be affected by earthquake vibrations, both local and far away.

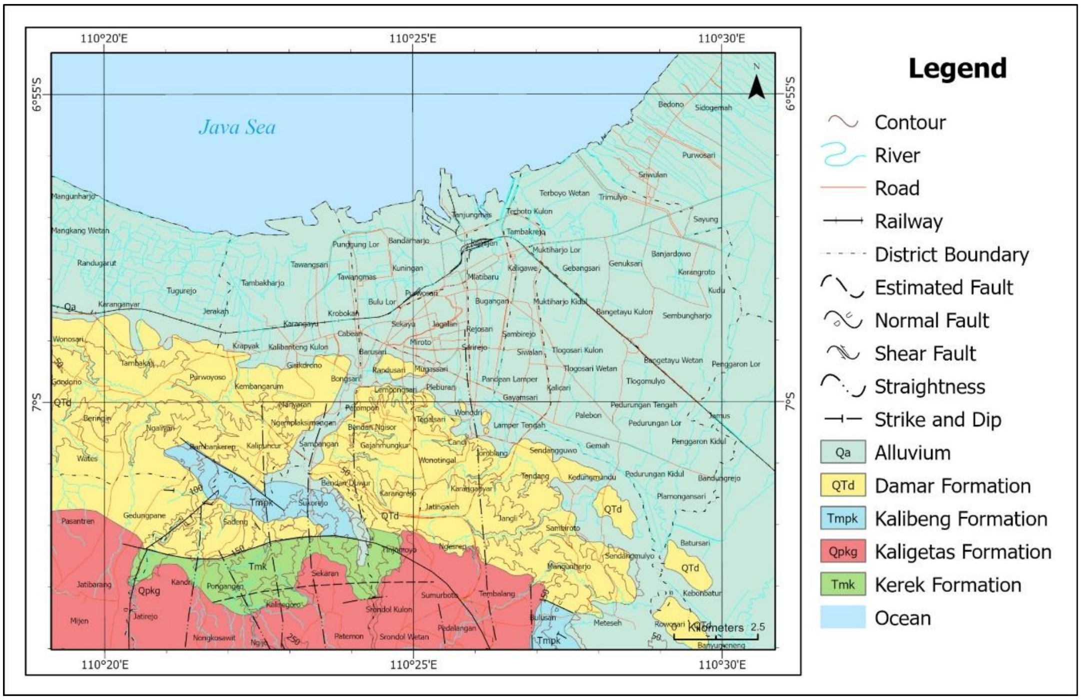

Fig. 1. Geological Map of Semarang City *(Thanden, et al., 1996 in Poejoprayitno, et al., 2008)*.

Based on earthquake catalog data from the *Pusat Vulkanologi dan Mitigasi Bencana Geologi* (PVMBG) (Supartoyo, et al., 2014), an earthquake measuring VI to VII MMI occurred in Semarang on January 19, 1856, which caused damage to buildings. The earthquake may be associated with a fault in the Semarang area and is suspected to be active or potentially active in the future.

The HVSR (Horizontal to Vertical Spectral Ratio) is a method commonly used for three-component micro tremor to determine bedrock depth. The parameters used in this method are the amplification factor and natural frequency. Both of these parameters are related to the subsurface physical parameters to identify the geological characteristics of the research area. The HVSR method uses the principle of calculating the spectral ratio resulting from the sum of the horizontal and vertical components (Nakamura, 1989). The value of the amplification factor of a place can be known from the height of the spectral peak of the HVSR curve as a result of micro tremor measurements at that place. The dominant period value or dominant frequency obtained from the HVSR curve has a correlation with the thickness level of the sediment layer (Nakamura, 2008).

Semarang City is an area that is included in the category of a moderate disaster-prone category with a disaster risk index of 183,6 (high level) in 2015 and 120,75 (moderate level) in 2018 (IRBI, 2018). The previous studies shown that the coastal area of Semarang experienced many disasters such as sea water intrusion (Suhartono, et al., 2013, Setyawan, et al., 2016, Supriyadi, et al., 2013, 2016, Wijatno, et al., 2019), tidal flood (Kuriawan, 2003, Wahyudi, 2007, Bakti, 2010, Ramadhani, et al., 2012, Handoyo, et al.,, 2016) and land subsidence (Marsudi, 2000, Suhelmi, 2012, Supriyadi, et al., 2009, Abidin, et al., 2010, 2012, Widada, et al., 2020). However, the vulnerability to the earthquake disaster has not been discussed in the previous study. Thus, it is necessary to study the mitigation of several disasters in the city of Semarang, including earthquakes, and efforts in the context of disaster management. According to Law Number 24 of 2007 concerning Disaster Management, several actions that can be taken in disaster management include prevention, mitigation, preparedness, and response to emergencies. One of the most important steps is disaster mitigation. In the context of disaster risk reduction, on this occasion, we will discuss the micro zonation of earthquake vulnerability in the coastal area of Semarang. It is important to create a zonation for earthquake vulnerability for mitigation because the Semarang Coastal area is the center of activity for government offices, private offices, hotels, industries, services and also housing.

2. RESEARCH METHODS

2.1. Location of data collection

The type of research carried out by acquisition data in the form of measuring micro tremor signals in the form of transient seismic signals with time domain. Data collection was carried out in the Semarang Coastal area, in UTM coordinates, with boundaries Easting 432000-443000 and Northing 9226000-9233000, as shown in **figure 2**.

Data collection was carried out with a semi-grid distribution with a west-east distance of about 500 m and a north-south distance of approx. 1000 m, with the measurement point located around the existing road. Measurement of the micro tremor signal with a 3-component digital seismograph TDS type 303S and recording with a midi data logger type GL 240. Installation of the north direction of the seismograph with a geological compass, data collection for each point for 10 minutes with a sampling rate of 20 Hz. In this study, 110 data points were successfully taken and carried out in February 2020 (Irham, et al., 2021a, b).

The obtained micro tremor data is then converted into .txt format with notepad ++, then the data can be processed with geopsy software to obtain amplification (A_0) and pre dominant frequency (f_0) values. From the values of frequency dominant (f_0), amplification (A_0), Seismic Vulnerability Index (SVI), Peak Ground Acceleration (PGA) and Ground Stress Strain (GSS) can be calculated using the equations described above using Microsoft Excel software. The A_0, f_0, SVI, PGA and GSS data were then plotted into a base map using the ArcGIS software to describe the distribution of these values (Irham, et al., 2021b). The equation for calculating (f_0) and (A_0), the values of SVI, PGA and GSS is described in the next sub-section.

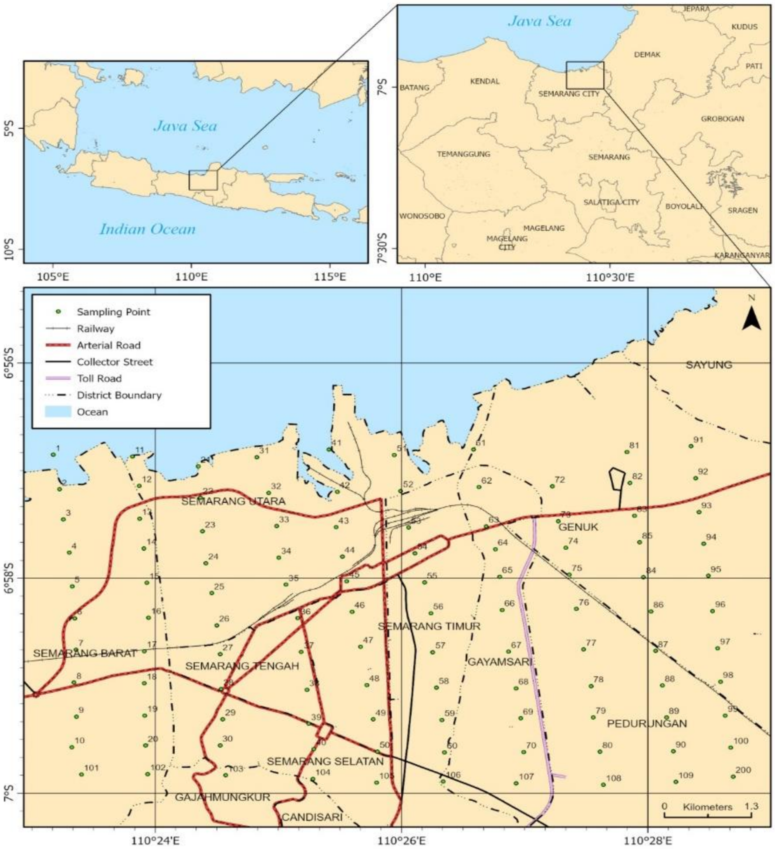

Fig. 2. Location of the research area.

2.2. Dominant frequency and amplification

The dominant frequency is the frequency value that is often recorded when measuring micro tremor signals. The dominant frequency can be considered as the frequency value of the rock layer which can indicate the type and nature of the rock at that point. The dominant frequency value of an area is influenced by the thickness of the sediment layer above the bedrock and the average velocity of the shear wave in that layer. The magnitude of the dominant frequency can be formulated in the following equation (1), Nakamura (1997):

$$f_0 = \frac{v_s}{4h} \tag{1}$$

where v_s is the shear wave velocity of the sediment layer and h is the bedrock depth.

Lachet and Brad (1994) used six simple tectonic models to perform combined simulated tests of contrast changes in shear wave velocity and soil layer thickness. The simulation results show that the peak frequency values change along with changes in geological conditions. From f_o, we can classify the soil types based on the criterion of Kanai (1983) as described in **table 1**. Nakamura (2000) states that the value of the strengthening factor or soil amplification is related to the impedance contrast ratio of the surface layer to the layer below it. If the impedance contrast ratio of the two layers is high, the gain factor value is also high, and vice versa. Arifin (2014) states that the amplification value is directly proportional to the value of the horizontal and vertical spectrum ratio (H/V). The amplification value can increase if the rock has undergone deformation (weathering, folding, or faulting) that changes the physical properties of the rock. In the same rock, the amplification value can vary according to the degree of deformation and weathering of the rock body. Amplification can be formulated with the equation (Arifin, et al., 2014):

$$A_o = \frac{\rho_b v_b}{\rho_S v_s} \quad (2)$$

where b is the density of bedrock (g/cc), v_b is the velocity of wave propagation in the bedrock (m/s), s is the density of soft rock (g/cc) and v_s is the velocity of wave propagation in sedimentary rock (m/s). dt).

Table 1.

Soil Classification based on Dominant Frequency Values (Kanai, 1983).

Soil Clasification Type	Natural Frequency (Hz)	Kanai's Clasification
Type I	6.67 – 20	Tertiary rocks or older. Consist of hard sandy rocks, gravel, etc.
Type II	4 – 6.67	Alluvial Rock, with thickness of 5m, consist of sandy-gravel, sandy hard clay, loam, etc.
Type III	2.5 – 4	Alluvial Rock, with thickness >5m, consist of sandy-gravel, sandy hard clay, loam, etc.
Type IV	< 2.5	Alluvial Rock, originated from top soil delta sedimentation, mud, etc. With Thickness of 30 or more

Amplification is a magnification of seismic waves that occurs due to significant differences in velocity and density between layers. Seismic waves will experience amplification if they propagate from one medium to another medium that is softer than the previous medium. The greater the difference, the greater the magnification experienced by the wave. The amplification values can be grouped as in **table 2** (BMKG in Setiawan, 2009).

Table 2.

Classification of amplification factors (BMKG in Setiawan, 2009).

Zone	Classificatin	Amplification factor value
1	low	A<3
2	medium	3≤A<6
3	high	6≤A<9
4	Very high	A≥9

2.3. Peak Ground Accelleration

Peak Ground Acceleration (PGA) is the greatest value of ground acceleration at a place caused by earthquake vibrations in a certain period of time. The value of ground vibration acceleration that will be taken into account as one part in planning an earthquake-resistant building is the maximum ground acceleration value (Ehsani, 2015). The geological conditions of the soil and the level of sediment compaction in an area greatly determine the size of the PGA value. The more compacted the sediment, the smaller the PGA value in the area.

The PGA value in an area can be measured directly with a PGA measuring device but can also be approximated empirically. There are many empirical approach formulas to calculate the PGA value, but in this study the formula from Kanai (1966) in Douglas (2022) is used, because this formula takes into account the strength of the earthquake in the SR and the distance from the epicenter and the dominant period (T) in the research area being studied.

$$\mathrm{PGA} = \frac{5}{\sqrt{\mathrm{To}}}\, 10^{0{,}6\mathrm{M} - \mathrm{p}\log\mathrm{R} + \left(0{,}167 - \frac{1{,}88}{\mathrm{R}}\right)} \quad (3)$$

where PGA is the maximum ground acceleration (cm/s^2), To is the dominant period (s), M is the earthquake magnitude on the Richter Scale (SR), R is the distance from the hypocenter to the measurement point (km), and p is (1.66 + 3.6R). In this study, we used parameters Yogyakarta earthquake data on 27 May 2006.

2.4. Seismic Vulnerability Index

Seismic Vulnerability Index (SVI) can be interpreted as a parameter that can be used to determine the level of vulnerability of an area to the threat of earthquake risk. The seismic susceptibility index with earthquake risk level against earthquake damage shows a linear relationship

(Nakamura, 2008). The value of the seismic vulnerability index at each measuring point is obtained by squaring the amplification value (A_0) and then divided by the dominant frequency value (f_0) obtained in the HVSR spectrum as shown in equation (4) (Nakamura, 1997).

$$\mathrm{SVI} = \frac{\mathrm{A}_0^2}{\mathrm{f}_0} x 10^{-6} \quad (4)$$

where SVI is the Seismic Vulnerability Index (s^2/cm), A_0 is the Amplification and f_0 is the dominant frequency (Hz).

2.5. Ground Stress Strain

GSS (Ground Stress Strain) is the ability of the soil layer material to stretch and shift during the Nakamura earthquake (2000). Areas that have a high GSS value have a high risk of ground motion due to earthquakes, such as land subsidence, ground shaking, and ground stretching. The GSS value and its effect on dynamic soil properties can be summarized in **table 3**. In calculating the GSS of the surface soil layer in an area when an earthquake occurs, it can be done by multiplying the seismic vulnerability index with the maximum soil acceleration which is formulated as in equation (5), (Nakamura, 1997, 2008).

$$GSS = SVIxPGA \quad (5)$$

where SVI is Seismic Vulnerability Index (s^2/cm) and PGA is Peak Ground Acceleration (cm/s^2).

Table 3.

Strain Dependence of Dynamic Properties of Soil (Nakamura, 1996).

Size of strain *(GSS)*	**10^{-6} 10^{-5}**	**10^{-4} 10^{-3}**	**10^{-2} 10^{-1}**
Phenomena	Wave, vibration	Crack, Diff, Settlement	Landslide, Soil compaction, Liquefaction
Dynamic proterties	Elasticity	Elasto-Plasticity	Repeat–Efect, Speed-Effect of loading

3. RESULT AND DISCUSSION

3.1. Dominant frequency and amplification

The dominant frequency of the study area as shown in **figure 3** varies from 0.13 Hz - 7.47 Hz, it can be grouped into 3 categories, namely type IV (0 Hz - 2.5 Hz), type III (2.5 Hz - 4 Hz), and type II (4 Hz-10Hz). In general, almost 90% of the dominant frequencies in the study area are type IV frequencies (low type) which indicates that the sediment in the study area has a thickness of more than 30 m. Some areas have a dominant frequency of type III which are around Candisari and Milo, with a thickness of 10 m - 20 m, while areas that have a dominant frequency of type II are around Candisari and Milo with a thickness of 5 m - 10 m. The amplification map of the research area is shown in **figure 4**. The amplification values ranged from 0.13-5.96. According to Setiawan (2009) (**Table 2**), the amplification values can be grouped into 2, namely low amplification ($A < 3$) (in **figure 4** shown in blue) which is mostly located in the middle of the study area, and moderate amplification ($3<A<6$) (in **figure 4** is shown in white) which is located in West Semarang District, North Semarang District, Genuk District, and Sayung District and locally around South Semarang District, Gajahmungkur District, and Mranggen District. The amplification value shows the contrast between the sedimentary layer and the bedrock layer, the higher the contrast, the greater the amplification. The amplification value is influenced by the contrast value of wave velocity and rock density. A low wave speed will have a high amplification which tends to have a low density so that in the event of an earthquake the risk is higher than in an area with small amplification. Small amplification values are usually associated with a small contrast between sediment and bedrock, meaning that sedimentary rocks are denser and seismic waves will propagate faster so they have less risk of earthquakes.

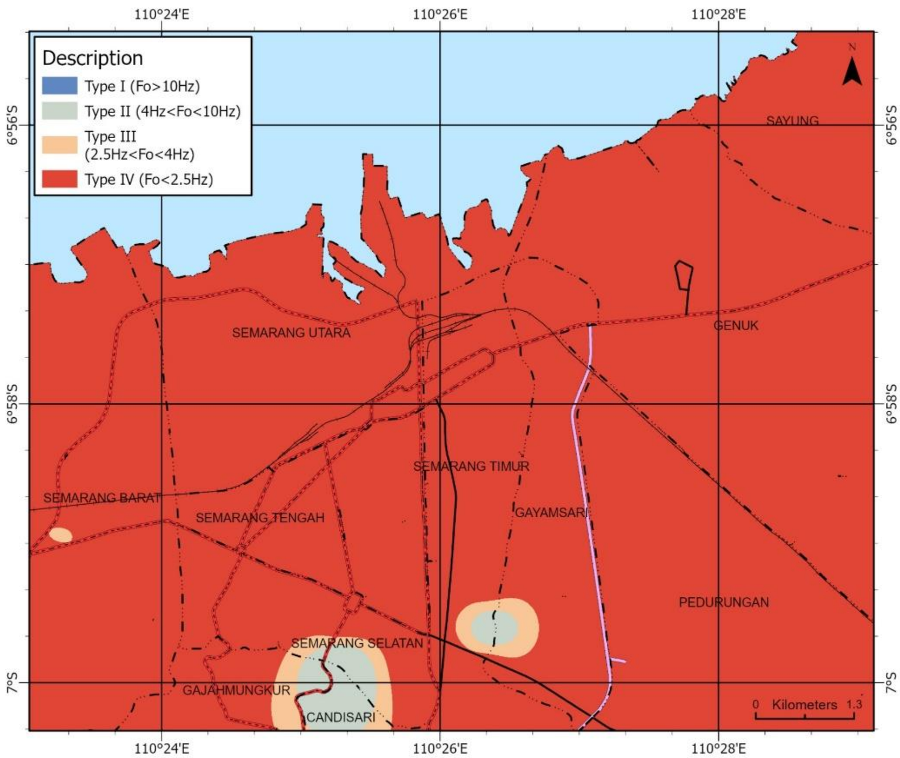

Fig. 3. Dominant Frequency Map of Semarang Coastal Area.

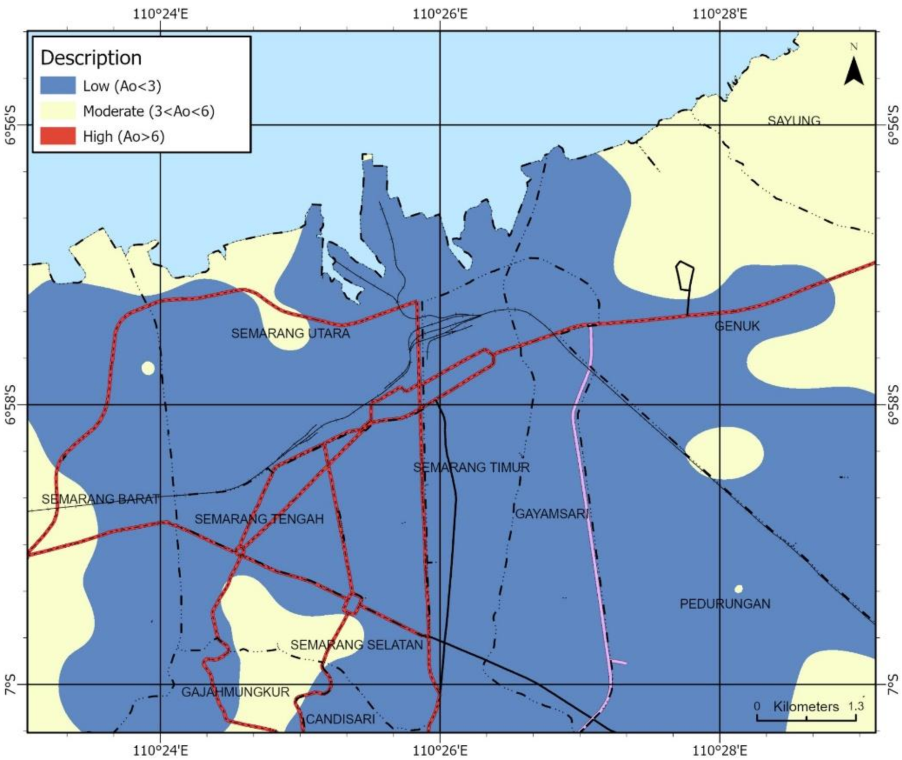

Fig. 4. Amplification map of Semarang Coastal Area.

3.2. Peak Ground Acceleration (PGA)

The PGA (Peak Ground Acceleration) value is calculated using the Kanai equation (1966 in Douglas 2022) as shown in equation (3) with input parameters: dominant period (T), earthquake strength (M), and epicenter distance (R). The distribution of PGA values in the research area with the source of the Yogyakarta earthquake on 27 May 2006 with a strength (M) of 5.9 SR and an epicenter distance of about 105 km - 120 km is shown in **figure 5**, the PGA value varies between 5.53 gal - 44.15 gal which corresponds to with grades II-VI on the MMI scale.

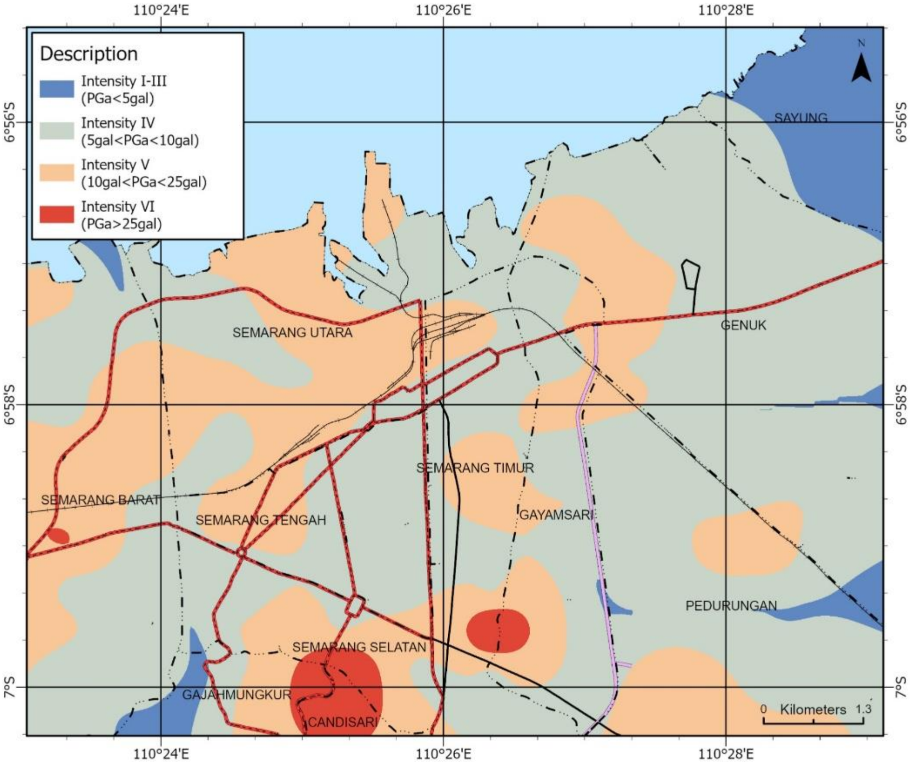

Fig. 5. Peak Ground Acceleration Map of Semarang Coastal Area.

PGA values were grouped into 4 levels with very weak PGA (PGA < 5gal), weak PGA (5<PGA<10 gal), moderate PGA (10<PGA<25 gal), and moderately strong PGA (PGA>25 gal).

Areas with very weak PGA are in the west of Gajahmungkur, to the east of Pedurungan and in Sayung, areas with weak PGA are in the eastern and northern parts of West Semarang, western and eastern North Semarang, Gayamsari District, Pedurungan District, Mranggen District, and Genuk District. During the Yogyakarta earthquake on 27 May 2006, the buildings that are built on the less dense soil structures (i.e.,large PGA values) were areas that suffered severe damage in Bantul (Walter et al., 2008).

3.3. Seismic Vulnerability Index (SVI)

Seismic Vulnerability index (SVI) is calculated based on the Nakamura (2008) approach as shown in equation (4). The SVI value is shown in **figure 6** which varies between 0.41 cm^2/s – 140.27 cm^2/s. Based on Daryono (2014) in this study, SVI values were grouped into 3 parts, namely low SVI (SVI < 5), moderate SVI (5 <SVI < 25) and high SVI (SVI > 25). The higher SVI value indicates the lower level of stability of the sediment structure below the surface, so that if an earthquake occurs, there is a greater risk of damage. Areas with low SVI values are located locally in the central part of the research area, areas with moderate SVI values are almost dominant in the research area covering the central part of West Semarang Sub-District, South Semarang District, North Semarang district, Candisari district, East Semarang district, Gayamsari District , Pedurungan District and Mranggen District. Meanwhile, areas with high SVI values are located in the northern and southern parts of West Semarang Sub-District, Gajah Mungkur District, South Semarang District, Sayung District and Genuk District. Concerning the case of the Yogyakarta earthquakes on 26 May 2006 in Bantul, the area with more than 20 SVI was the most impacted area with the highest number of casualties, the material collapses, and fatalities (Daryono et al., 2009). Therefore, stakeholders and third parties should monitor the area with 25 SVI in the present study (red color in **figure 6**). Massive socialization regarding earthquake vulnerability must be implemented in local society to mitigate the possible future impacts.

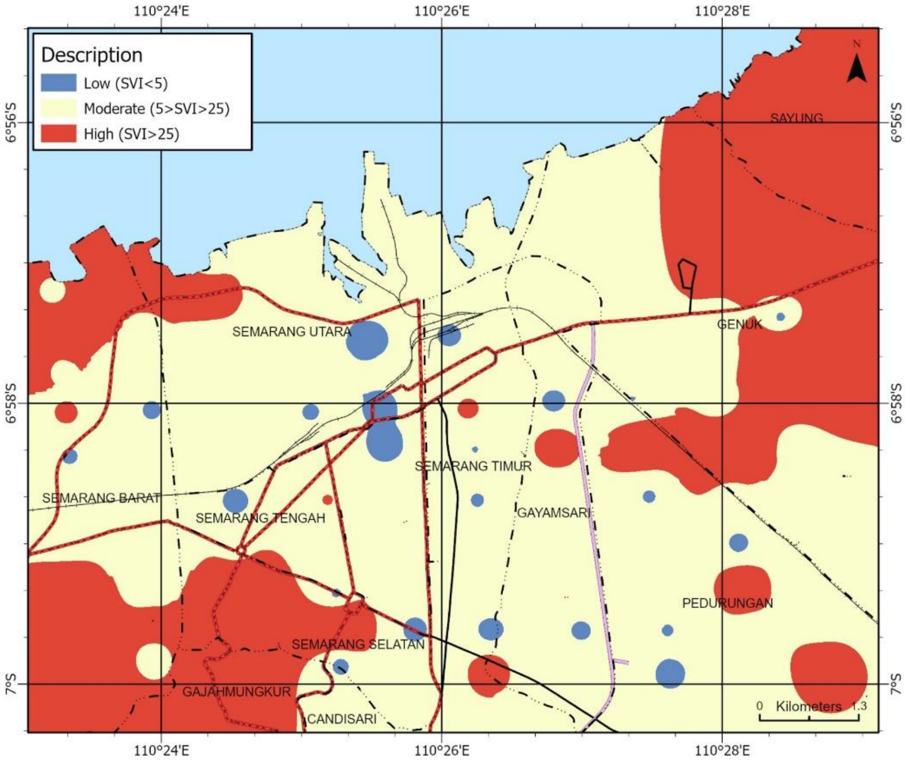

Fig. 6. Seismic Vulnerability index Map of Semarang Coastal Area.

3.4. Ground Stress-Starain (GSS)

Microzonation vulnerabilty to earthquake can be represent by ground shear strain (GSS). GSS is the ability of a material to stretch or shift during an earthquake. Ground shear strain has a relationship with the condition of the soil surface layer. The greater the ground shear strain value, the soil surface layer will be easily deformed, while the small ground shear strain value indicates the soil layer will be more difficult to deform. The distribution of GSS values in the study area is shown in **figure 7** with values varying between $12.3x10^{-6}$ – $788x10^{-6}$. The GSS value in the study was grouped into three groups, namely low ($GSS < 10^{-4}$), medium GSS value ($10^{-4} < GSS < 10^{-3}$) and high GSS value ($10^{-3} < GSS < 10^{-2}$). Based on the classification of Nakamura (1998), the occurrence of earthquake in Semarang City will cause crack, diff, settlement and soil compaction. Thus, earthquake may worsen the subsidence rate in the coastal area of Semarang.

Zones with low susceptibility to earthquakes are in the central part of the study area shown in blue (**figure 7**), namely in the central part of West Semarang District, the southern part of North Semarang District, the northern part of South Semarang District, the northern part of Gajah Mungkur District, Candisari District, the northern part of East Semarang District, the northern part of Gayamsari District and the western part of Pedurungan District.

Zones with moderate vulnerability are in the western, northern and eastern parts of the study area which are shown in brownish white (**figure 7**). Zones with moderate vulnerability are in West Semarang District, northern North Semarang District, Gajahmungkur District, South Semarang District, northern East Semarang District, northern Gayamsari District, Genuk District, Pedurungan District and Sayung District. There are almost no areas with high vulnerability in the study area.

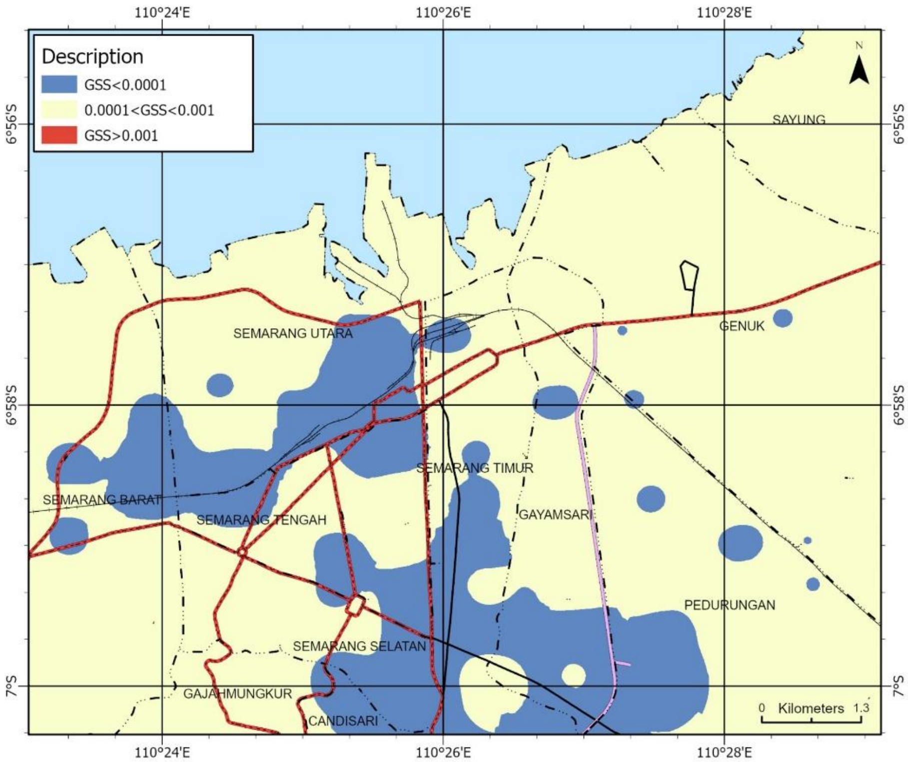

Fig. 7. Ground Stress-Strain Map of Semarang Coastal Area.

4. CONCLUSIONS

The vulnerability level of the Semarang coastal area to earthquakes is classified into weak, moderate, and strong categories. However, based on the ground shear strain (GSS), most of the study area is dominated by the moderate vulnerability. In contrast, several parts of the north to south of Semarang City are weakly vulnerable to earthquakes i.e., central part of West Semarang District, the southern part of North Semarang District, the northern part of South Semarang District, the northern part of Gajah Mungkur District, Candisari District, the northern part of East Semarang District, the northern part of Gayamsari District and the western part of Pedurungan District. Thus, massive socialization is very important to be conducted especially for the people living in the moderate to strong categories of earthquake vulnerability to mitigate the future eartquake impact. It is very important to be noted that, this study was conducted during the dry season. It is very important to collect data during the rainy season to investigate the possibility of its seasonal effect. This task is left for future study.

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