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Yusran Asnawi, Umar Muksin, Yuni Putri Tarniati, et al.

Seismic Vulnerability Based on Microtremor Data and HVSR Method in Krueng Raya, Aceh Besar

Yusran Asnawi[1, 2], Umar Muksin[3, 4, a)], Yuni Putri Tarniati[4], Andrean VH Simanjuntak[5], Syamsul Rizal[2], Muhammad Syukri[4]

[1] *Universitas Islam Negeri Ar-Raniry, Banda Aceh Indonesia*
[2] *Doctoral Program of Mathematics and Applied Sciences, Universitas Syiah Kuala, Indonesia*
[3] *Tsunami and Disaster Mitigation Research Center (TDMRC), Universitas Syiah Kuala, Indonesia*
[4] *Department of Physics, Universitas Syiah Kuala, Banda Aceh, Indonesia*
[5] *Meteorological, Climatological, and Geophysical Agency, BMKG, Banda Aceh, Indonesia*

[a)] Corresponding author: muksin.umar@unsyiah.ac.id

Abstract. Geology Krueng Raya, Aceh Besar is formed from thick sediment and hard rock consisting of young alluvium and volcanic rock. The study area is characterized by the Seulimeum fault which is recently very active in generating earthquakes. This study aims to analyze microtremor data to determine the value of the seismic vulnerability index in the Krueng Raya area, Aceh Besar. Data acquisition was carried out at 20 measurement points located across the Mesjid Raya District. The data were analyzed using the Horizontal to Vertical Spectral Ratio (HVSR) method. Based on the dominant frequency value and the amplification value, the seismic vulnerability index value in the Krueng Raya area ranges from 0.20 to 12.92 which is categorized as low to moderate. Areas that have low seismic vulnerability index values are in the villages of Lamreh. Areas with a moderate seismic vulnerability index value are Meunasah Kulam Village, and Paya Kameng Village.

INTRODUCTION

The Aceh region consists several active faults such as the 120 km long Seulimeum Fault and the 200 km Aceh Segment. The Aceh Meteorology, Climatology and Geophysics Agency [1] reported the history of the 2020-2021 Aceh earthquake in the Seulimeum Fault area on December 5, 2020, with a magnitude of Mw 5.5, November 14, 2020, with an M 5.3 and January 7, 2021, with an M 5.0 (See Figure 1 [1]). Historically, earthquakes occurred along the northern part of the Acveh Segment with a magnitude of M 6.5 [2,3] and along middle part of segment with a magnitude of M 6.0 [4,5].

Krueng Raya, Aceh Besar is one of the areas traversed by the Seulimeum Fault. The Seulimeum fault is a secondary fault that extends from Manee-Tangse to Pulau Weh in Sabang. The history of earthquakes was reported to have occurred in 1936 at a scale of M 7.2 [6] and in 1965 at a scale of M 6.5 in the Krueng Raya area [7]. According to Ito et al., [8] , the rare occurrence of earthquakes in areas with active faults is feared to have the potential to cause earthquakes with a magnitude of M 7.0. The existence of the Seulimeum Fault is accompanied by the presence of the Seulawah Agam volcano with the acquisition of 20 Pliocene deposit movements as far as 20 km northwest [7]. Based on the geological map from Bennet et al., [9] , the Aceh Besar region has a complex rock composition, composed of alluvium deposits, sedimentary rocks, meta sediments, intrusive igneous rocks, and volcanic rocks formed from the activity of the Seulawah Agam volcano.

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The level of risk of damage due to earthquakes is influenced by factors such as soil and rock characteristics. Soft sediment layers can cause amplification of seismic waves or shaking during earthquakes and cause damages [10,11]. Areas with high amplification values are categorized as earthquake-prone areas [12]. The results of the seismic vulnerability index Kg calculation can be used to estimate of a location to damage when an earthquake occurs [13]. Seismic vulnerability index analysis needs to be done to reduce the risk of being affected by earthquake shaking before infrastructure development is carried out. By using the horizontal to vertical spectral ratio (HVSR) method one can determine the level of distribution of soil and rock vulnerability in the Seulimeum Fault area, one of which is in Krueng Raya, Aceh Besar.

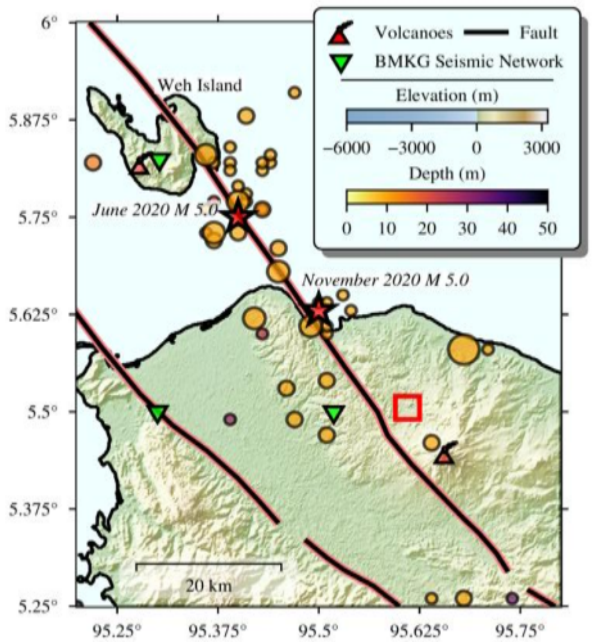

FIGURE 1. Historical earthquakes around the study area that felt by local peoples in the last decade.

GEOLOGICAL SETTINGS

Krueng Raya in terms of topography has a height of 100 to 400 meters above sea level (m asl). Based on the Geological Map Sheet Banda Aceh, Sumatera [14,15], this area has complex geological conditions, composed of sedimentary and meta-sedimentary rocks such as andesite, conglomerate and limestone, as well as volcanic formations consisting of rocks produced volcanic eruptions (piloclastic flows), and igneous rock intrusions. On the west side there are alluvial deposits consisting of gravel, sand, silt, and clay and on the south side there are volcanic deposits, these deposits are quaternary in the Holocene period. Deposits that are in the Holocene Quaternary are classified as young deposits according to geology, so the rocks are easy to lose and soft. The low-lying area is arranged as a beach that stretches in an almost northwest-southeast direction. The Quaternary Basin in the east is bounded by hills composed of Plio-Plistocene rocks originating from the Seulawah Agam volcano [16,17].

MICROTREMOR

Microtremor is a recorded seismic vibration originated all directions continuously with a very small value of amplitude [18]. Microtremor has an amplitude of less than 0.1-1.0 mm and an amplitude velocity of between 0.001

cm/s up to 0.01 cm/s [18,19]. Microtremor originating from the interaction between wind and trees with a frequency between 0.1 Hz – 1 Hz [20]. Microtremor is composed of a combination of surface waves, namely the Rayleigh and Love waves [21]. Microtremor can be recorded using a highly sensitive seismometer. The spectral features of microtremor show a correlation with the geological condition of an area [22]. From the microtremor data analysis we can determine the dynamic characteristics of the subsurface layer [18].

HORIZONTAL TO VERTICAL SPECTRAL RATIO (HVSR)

Horizontal to Vertical Spectral Ratio (HVSR) is one method to determine the dynamics characteristics of the soil surface layer. This method is effectively used to determine the dynamics of the soil layer in a large area. HVSR vibration are contributed by seismic surface waves [23]. This method produces a microtremor spectrum with a spectrum peak at the dominant frequency as shown in Figure 2. Dominant frequency values (f_0) and amplification (A) are parameters that provide information about seismic susceptibility and shaking levels compared to geological conditions [10,18]. The HVSR method can also be used to analyze small vibrations caused by earthquake which can then be used to identify the characteristics of a layer below the surface [10,18,24].

The values of the dominant frequency of an area can be used in the planning of earthquake-resistant buildings for earthquake mitigation purpose [10,25]. The higher the frequency of the wave, the shorter the range of depth reached by the seismic wave. A high dominant frequency value represents the condition of a thin sediment layer, which imply low seismic vulnerability of the area [22]. The seismic amplification is an increase of seismic wave shaking that occurs due to differences between layers of the soil surface. If the wave velocity and rock density are lower, the amplification value is higher [10,18,24]. The amplification value describes the constituent soil layers in the study area. An area composed of soft sediment will experience an increase in ground vibration. The greater the difference, the greater the amplification value [13].

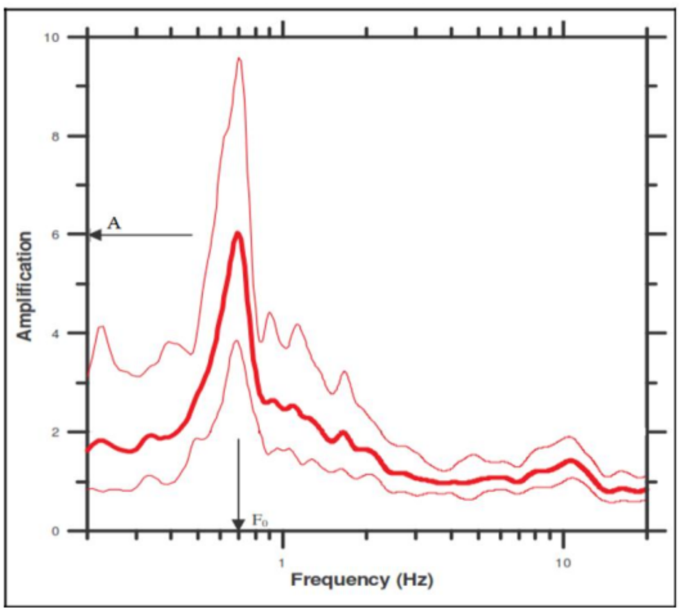

FIGURE 2. Microtremor spectrum from HVSR analysis (SESAME, 2004) [26]

SEISMIC VULNERABILITY INDEX

The seismic susceptibility index is obtained by squaring the peak value of the H/V microtremor spectrum or amplification divided by the dominant frequency as follow:

$$Kg = \frac{A^2}{f_0}$$

where Kg is the seismic vulnerability index at a location, A is the amplification value and f_0 is the dominant frequency value. Areas with low seismic vulnerability index have lower potential for damage during an earthquake occurrence. On the other hand, areas with a high seismic vulnerability index can experience high level of damages [12][10] caused by earthquakes.

The seismic vulnerability index (Kg) depends on the geological conditions of soil layer. Seismic vulnerability is an index that shows the level of vulnerability of the surface soil layer to deformation during an earthquake [10,12,17,23] . Subsurface constituent rocks affect the value of HVSR so that the microtremor spectra are differentiated based on their geomorphological conditions.

METHOD

Microtremor data measurements were carried out from January to March 2020 in Krueng Raya, Aceh Besar covering several villages around the Seulimum fault. The distribution of measurement points is 10 points with a distance between points of approximately ~500 m. Microtremor recording duration was carried out for 30 minutes with a sampling frequency of 100 Hz. Map of the location of the measurement points is shown in Figure 3.

The data acquisition in this study used a seismometer type S-20 Near Broadband seismic sensor with high sensitivity. The seismometer is placed on flat ground. The position of the seismometer is set to face geographic north using a compass as a reference. The three legs on the seismometer were adjusted by turning left or right, adjusted to the position of the air bubble on the nivo so that it is right in the middle (leveling). If the bubble is in the middle, it means that the tool is level with the ground. The connector cables from the seismometer, GPS antenna and Laptop USB were connected to the digitizer according to the instructions on the digitizer as shown in Figure 4. The GPS antenna is placed in an unobstructed place such as a tree, building or other. The power cable is connected to the digitizer for the operation of the seismometer and digitizer. The measurement is continued to the next point by following the same steps.

The amount of data in a microtremor recording is not the same, depending on the signal that falls into the data category. The better the signal, the more windowing was adjusted. Clean data from transient noise obtained from anti-triggering on filtered signal by comparing Short Term Average (STA) and Long Tern Average (LTA). STA, which is the average short-term amplitude value with a value of 0.5-2.0 seconds while LTA was set to 10 seconds. STA and LTA were driven continuously and if the value of the ratio between STA/LTA increases suddenly, it means that there was transient noise to be excluded. The analysis of the recommended number of windowing is 10 windows which are stationary (fixed) between 20 seconds to 50 seconds (SESAME, 2004) [26].

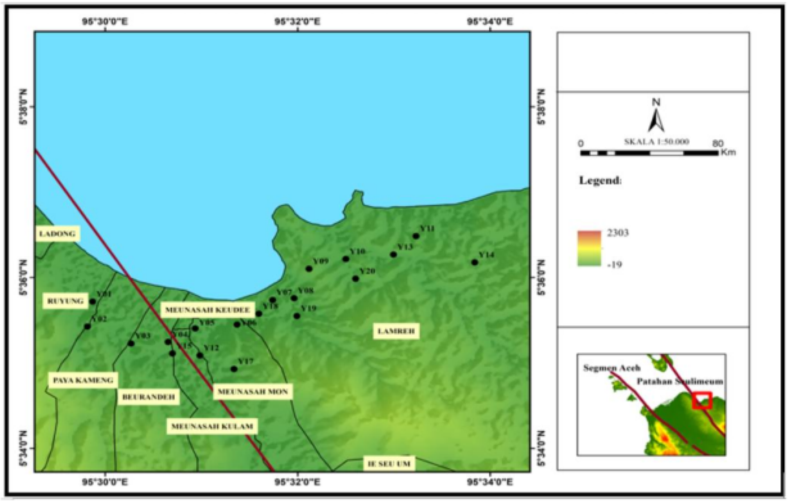

FIGURE 3. Map of the location of microtremor data measurement (± ~500 m)

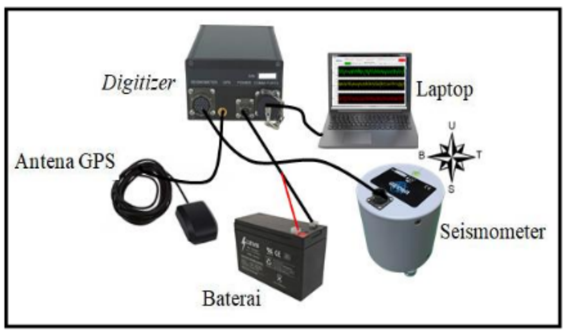

FIGURE 4. Microtremor data measurement scheme

The results of this study are the distribution of dominant frequency values, amplification, and seismic vulnerability index, so that the measurement results can be used to interpret the level of surface shock of a location in the event of an earthquake and can be used to determine earthquake prone area along the Seulimum fault.

RESULTS AND DISCUSSION

The results obtained based on the HVSR method were the dynamics of soil and rock characteristics based on the dominant frequency value (f0), amplification (A). We then calculated the seismic susceptibility index value (Kg). The H/V wave ratio is an indicator of seismic vulnerability in an area. The amplification value A was the maximum values of H/V while the dominant frequency is the frequency the H/V is maximum. The results of the data analysis including the values of the dominant frequency, the amplification, and the seismic vulnerability are shown in Table 1.

TABLE 1. The results of the HVSR data analysis

Survey	Coordinate		Data analysis		
	Latitude (N)	Longitude (E)	Dominant Frequency (F_0) (Hz)	Amplification (A_0)	Seismic Vulnerability Index (Kg)
Y03	5,587117	95,504529	2,255706	1,58922	1,11966
Y04	5,587421	95,510927	18,1095	1,94153	0,20815
Y05	5,5906722	95,515333	5,06942	1,02946	0,20903
Y06	5,590267	95,52173	11,2264	2,09558	0,391172
Y07	5,592172	95,527451	0,47806	0,67182	0,94411
Y08	5,595622	95,529025	1,21443	1,81932	2,725497
Y09	5,601702	95,535333	2,74952	1,61509	0,948717
Y12	5,584792	95,516424	1,27885	1,15772	1,048063
Y15	5,5835166	95,511688	3,3371	3,36364	3,390391
Y18	5,5959638	95,5327416	2,51756	4,11018	6,7102987
Y19	5,592487	95,533231	1,14965	0,81808	0,582139

TABLE 2. Classification of dominant frequency values in Krueng Raya according to Kanai, (1983) [22]

No	Point Location	Classification	Dominant Frequency (Hz)
1.	Paya Kameng	Type IV	0,45
2.	Meunasah Kulam	Type III - Type IV	1,27 -3,33
3.	Lamreh	Type III - Type IV	2,51 -9,98

TABLE 3. Krueng Raya Area Amplification Value Classification Zone

No	Point Location	Classification	Amplification Range (Hz)
1.	Paya Kameng	Low	2,42
2.	Meunasah Kulam	Moderate	1,16 - 3 ,36
3.	Lamreh	Low - Moderate	0,81 - 4,11

Dominant Frequency

The results of the microtremor data analysis shows that the dominant frequency is between 0.45 and 18.11 Hz. The low dominant frequency recordings are found at the measurement points Y07, Y08, Y12 and Y19 with a dominant frequency value of 0.45 to 1.27 Hz. The moderate dominant frequency values are at points Y03, Y09, Y15, and Y18 with a dominant frequency of 2.10 to 3.33 Hz. The high dominant frequency values are at points Y04, Y05, and Y06 with a dominant frequency value of 5.07-18.11 Hz. Areas with low dominant frequency records are associated with thick sediments. On the other hand, the high dominant frequency is interpreted as a relatively thin sediment layer.

The high values of dominant frequency were recorded in the hilly highlands, namely in the villages of Lamreh. Low-frequency recordings tend to be in low-lying areas close to residential areas and slope areas. The frequency value measured above the highlands is greater that that measured in the lower elevation area. The classification of the dominant frequency values for each measurement point is as shown in Table 2.

The dominant frequency record in Krueng Raya is shown in Table 2 including soil types I to Type IV. The average value of the dominant frequency is between 2.5 Hz and 4 Hz so that it is classified into type III soil. Type III soil consists of alluvial rock consisting of gravel sand, and clay. Soil type III is categorized as thick sediment with the thickness from 10 to 30 meters.

At points Y04 and Y06, the dominant frequency are between 7.79 and 18.10 Hz associated a sediment depth of 5 m. At points Y05, Y09, Y15, and Y180, the values of dominant frequency are between 4 - 10 Hz associated with 5 - 10 m thick sediment while at points Y03, Y07, Y08, Y12, and Y19 the dominant frequency are less than 2.5 Hz which interpreted as very thick sediment between 10 - 30 m. Based on the values of the dominant frequency, it shows that the research area has a dominant low to moderate earthquake shaking response. This is in accordance with the geological map in Krueng Raya Area, which mostly volcanic rocks in the form of hard and solid rocks.

HVSR Peak Spectrum Amplification

The results of the H/V spectrum analysis showed that the amplification value in Krueng Raya ranged from 0.67 to 4.11. The measurement point that has the lowest amplification is at point Y07 which has a value of 0.67 which is in the low elevation lands of residential residents located in Lamreh village and the point with moderate value are found at points Y15 and Y18 with values of 3.36 to 4.11. The high value at Y15 is due to the measurement data recorded around rice fields which are classified as loose soil. Infrastructure built above the loose type of soil eases to be damaged when an earthquake occurred. in Lamreh village the values of H/V was found moderate which relative safe for residential buildings.

High amplification values were identified as having a high risk of amplifying ground vibrations in the event of an earthquake. The amplification values at each measurement point location are classified based on their high and low values as shown in Table 3. Areas with low amplification values are in Paya Kameng villages, while areas with moderate amplification values are in Meunasah Kulam and Lamreh. The classification of the amplification risk zone in Krueng Raya has a low to moderate amplification. Low amplification values were obtained in slopes and highlands close to the sea, while moderate amplification values were obtained in low elevation lands close to river flowing rice fields.

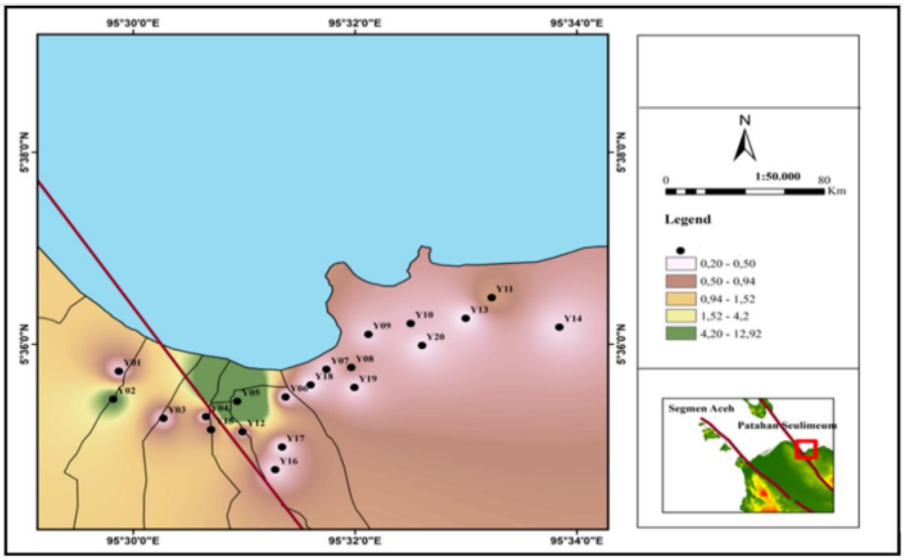

FIGURE 5. Map of distribution of seismic vulnerability index values in Krueng Raya

Seismic Vulnerability Index

The seismic susceptibility index level obtained is proportional to the amplification value and inversely proportional to the dominant frequency value. It is suggested that the higher the value of the vulnerability index (Kg), the higher the level of damage caused by the earthquake. The low seismic susceptibility index occurs at a high dominant frequency (f_0) with a low microtremor peak amplification spectrum [27, 28]. Variations in the value of the seismic vulnerability index are closely related to the geological and lithological conditions of the surrounding area, a high seismic vulnerability index is found on alluvial land, while in hilly areas it shows a low seismic vulnerability index [17].

The results of the calculation of the seismic susceptibility index based on soil and rock conditions against earthquake risk are classified as low to moderate with a value of around 0.27 to 4.20. Point Y18 has a value of 6.71 which is classified as high seismic vulnerability in the lowland area of the residents' residential yard. The area with a very high value of seismic vulnerability in Lamreh is associated with loose soil close to the river and rice filed.

The high vulnerability index from other points are at points Y02 and Y18 with the range of the values of 6.71 and 12.92 located in the villages of Paya Kameng and Meunasah Kulam. This region is potentially in high seismic hazard so that detailed study is required prior development. The lowest seismic vulnerability index was found at points Y07 and Y19 with values ranging from 0.58 to 0.94 located, indicating the impact of earthquake shaking is relatively low [29–32].

The level of earthquake risk in an area is commonly influenced by seismic factors, soil, and rock conditions in the area. Based on the geological composition, high seismic susceptibility was found in the land composed by rock alluvium. Areas with high seismic vulnerability index must pay more attention to building structures that are in accordance with the geological conditions so that the damage caused by earthquakes can be minimized [19,32].

TABLE 4. Classification of seismic vulnerability index values in Krueng Raya

No	Point Location	Classification	Vulnerability Index Range
1.	Paya Kameng	Very High	12.92
2.	Meunasah Kulam	Low – Moderate	1.04 – 3.39
3.	Lamreh	Low – Moderate	0.38 – 6.1

CONCLUSION

In general, the Krueng Raya area is characterized by low to medium level of seismic vulnerability level. The low values of seismic vulnerability are thin sedimentary rock. Only three specific regions were categorized as high level of seismic hazards which includes Lamreh, Meunasah Kulam and Paya Kameng. The areas with low values of seismic vulnerability correlate well with solid soil and hard rock as found by geologist and from direct observation. It is suggested that the area is suitable for tall buildings with careful detailed investigation prior development.

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