A MICROTREMOR SURVEY TO IDENTIFY SEISMIC VULNERABILITY AROUND BANDA ACEH USING HVSR ANALYSIS

Yusran Asnawi[*], Andrean V. H. Simanjuntak[**], Muksin Umar[***], Syamsul Rizal[****], Muhammad Syukri[*****]

[*]*Graduate School of Mathematics and Applied Science, Universitas Syiah Kuala, Banda Aceh, Indonesia*
[*]*Education of Information Technology Department, Universitas Islam Negeri Ar-Raniry, Aceh, Indonesia, yusran@ar-raniry.ac.id*
[**]*Badan Meteorologi Klimatologi dan Geofisika (BMKG), Aceh, Indonesia, andreansimanjuntak@gmail.com*
[***]*Physics Department, Universitas Syiah Kuala, Banda Aceh, Indonesia, muksin.umar@unsyiah.ac.id*
[****]*Graduate School of Mathematics and Applied Science, Universitas Syiah Kuala, Banda Aceh, Indonesia samsul_r@yahoo.com*
[*****]*Physics Department, Universitas Syiah Kuala, Banda Aceh, Indonesia, m.syukri@gmail.com*

Email Correspondence : andreansimanjuntak@gmail.com

Abstract: Banda Aceh can be categorized as an earthquake-prone city because of the existence of two active segments namely Seulimeum and Aceh. Both segments are considered to provide great potential damage in the future. In this article, we conduct a microtremor survey in the Peukan Bada, sub-part of Banda Aceh city, to learn the vulnerability level and support disaster mitigation plan. A total of 20 sites were measured with a seismometer to record the seismic waveform. The waveform was recorded in 45 minutes with a sampling rate of 100 sps and has analyzed using the horizontal-vertical spectrum ratio (HVSR). The results obtained are the dominant parameters, such as the period with a range of $0 - 0.5$s, frequency with a range of $0 - 6$ Hz, seismicity vulnerability index with a range of $0.1 - 0.5$. The result was relevant to the geological conditions of Peukan Bada that dominated by alluvial rocks and mud sediments. The level of vulnerability ($K_g > 1.0$) obtained is quite high and proportional to the soil type that can amplify the seismic waveform. The results obtained are expected to be a supporting study of disaster mitigation and understand the geological conditions of Banda Aceh in terms of seismic vulnerability.
Keywords: microtremor; seismic; susceptibility; alluvial; dominant parameter

Abstrak: Banda Aceh dapat dikategorikan sebagai kota rawan gempa karena adanya dua segmen aktif yaitu Seulimeum dan Aceh. Kedua segmen tersebut bisa memberikan potensi kerusakan yang besar di masa mendatang. Pada tulisan ini, kami melakukan survei mikrotremor di Kecamatan Peukan Bada, salah satu sub-wilayah kota Banda Aceh, untuk mempelajari tingkat kerentanan dan mendukung rencana mitigasi bencana. Sebanyak 20 lokasi diukur dengan seismometer untuk merekam bentuk gelombang seismik. Gelombang direkam selama 45 menit dengan jumlah sampel 100 sps dan dianalisis menggunakan *horizontal-vertical spectrum ratio* (HVSR). Hasil yang diperoleh adalah parameter yang dominan yaitu periode dengan rentang $0 - 0.5$s, frekuensi dengan range $0 - 6$ Hz, indeks kerentanan kegempaan dengan rentang $0.1 - 0.5$. Hasil tersebut relevan dengan kondisi geologi Peukan Bada yang didominasi oleh batuan aluvial dan endapan lumpur. Tingkat kerentanan ($K_g > 1.0$) yang diperoleh

cukup tinggi dan sebanding dengan jenis tanah yang dapat memperbesar gelombang seismik. Hasil yang diperoleh diharapkan dapat menjadi pendukung kajian mitigasi bencana dan memahami kondisi geologi Banda Aceh dari segi kerentanan seismik.
Kata kunci: mikrotremor; seismik; kerentanan; alluvial; parameter dominan

Introduction

Banda Aceh can be categorized as the earthquake-prone city in Indonesia because of the actively local tectonic process. The process is mostly influenced by two active segments namely Seulimeum in the NE part and Aceh in the SW part during Cenozoic (Sieh and Natawidjaja, 2000; McCaffrey, 2009; Craig and Copley, 2018; Muzli et al., 2018; Muksin et al., 2019). Both segments have potential magnitude ± 6.0 with a slip rate of 2.2 - 2.5 cm/year (Ito et al., 2012; Simanjuntak and Olymphia, 2017; Bradley et al., 2017; Tong et al., 2018).

The last felt earthquake has occurred in 1964 with M 6.5 in the Seulimeum segment (Hurukawa and Biana, 2014, Rusydy et al., 2020). In other hands, Banda Aceh is also included in the high seismic hazard zone with acceleration peak of 0.3 - 0.4 g in bedrock for a return period of 475 years (Omang et al., 2017; Irsyam, 2017; Triyoso et al., 2020).

The seismic hazard condition in Banda Aceh is supported by the geological condition that has a thick alluvial soil as the subsurface material which stand on a basin area (Rusydy et al., 2020, Asrillah et al., 2020). Therefore, the seismic surface waveform in the basin sediment can be amplified up to 1.5 to 2.0 times greater than the normal recording (Irsyam, 2017; Simanjuntak et al., 2018; Cipta et al., 2018). Furthermore, geomorphological studies of destructive earthquakes show the highest levels of the risk occurring in the basin with alluvial sediment (Nakamura, et al., 2019; Papadopoulos et al., 2020; Ali and Ali, 2020).

One of the most important events, the 2004 earthquake (Mw 9.0), occurred in the subduction zone and caused massive damage and losses in Banda Aceh which stand on the basin (Asrillah et al., 2020). From earthquakes historical, a disaster mitigation program must have been carried out to highlight the earthquake risk in Banda Aceh. To support the program, we conduct a microtremor study to learn the soil vulnerability in Banda Aceh.

Many microtremor studies have been applied by using the HVSR method to highlight the subsurface soil thickness and disaster mitigation study. For example, soil evaluation after the earthquake (Ren et al., 2017), site amplification (Stanko et al., 2019; Akaya and Ozvan, 2019), micro zonation (Gosar, 2017;

Yusran et al., 2020) and sedimentary structures (Cipta et al., 2018; Kang et al., 2020).

Microtremor utilizes the ratio of ambient noise (ground vibration from human and natural activities) on horizontal and vertical components to describe the subsurface structures. The subsurface structure characteristics have been determined by looking for surface dynamic characteristics, such as dominant frequency (f_0), amplification factor (A), and seismic susceptibility index (K_g).

In this research, we conduct a specific study for one sub-district in Banda Aceh, namely Peukan Bada. The results are used to find the seismic vulnerability index (K_g). With a seismic vulnerability index, infrastructure planning and development in an area can be carried out following soil conditions and implementing disaster mitigation (Vessia et al., 2020).

Tectonic and Geology

The local seismic activity around Banda Aceh is mostly influenced by Aceh and Seulimum segments that met in Tangse. Aceh segment stretches from Tangse to Aceh Island (covering Pidie and Banda Aceh regions). Meanwhile, Seulimeum Segment extends from Tangse through Seulawah Area to Sabang (Omang et al., 2017; Muzli et al., 2018; Muksin et al., 2019) as shown in figure 1.
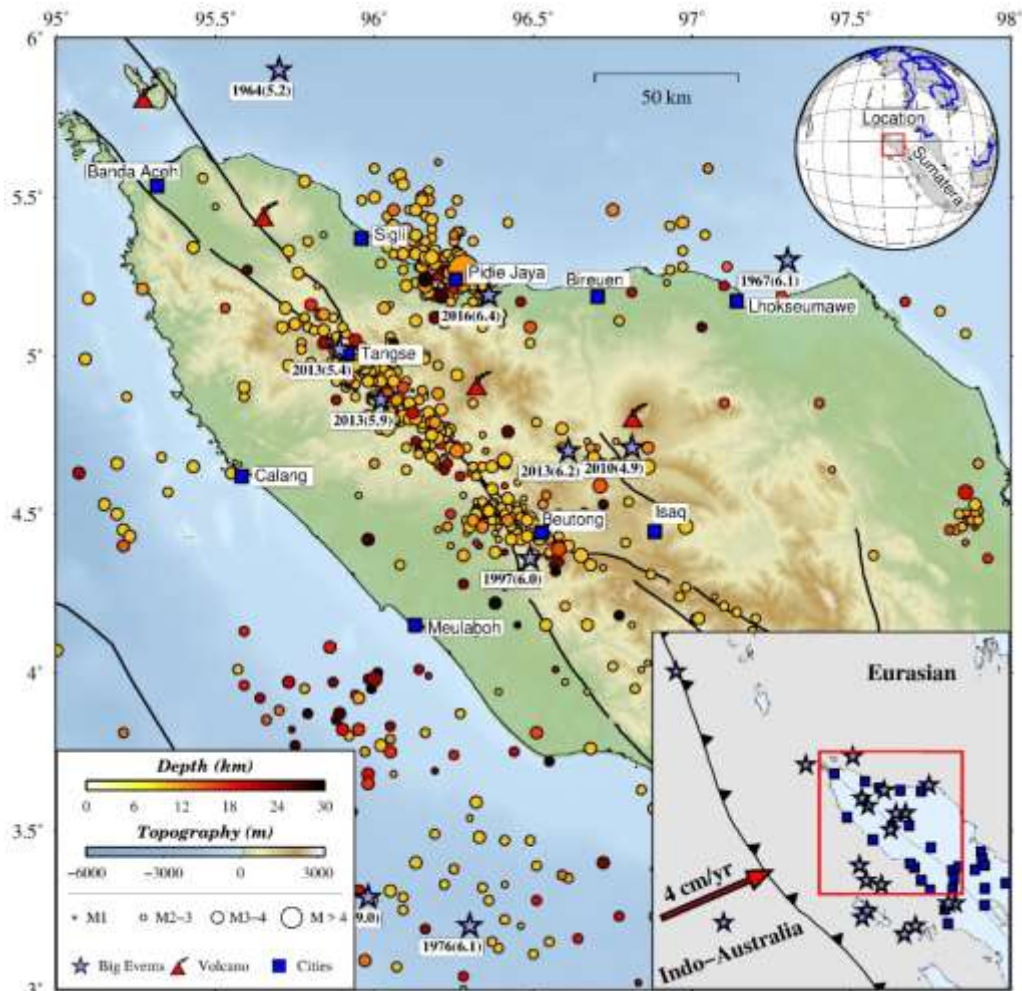
Figure 1. Historical map of significant earthquakes that felt in Banda Aceh in 1964 – 2020.

Aceh segment can be included as one of the most important faults because it has not produced an earthquake for a long time and potential to generate M > 6 (Simanjuntak et al., 2017, Ito et al., 2012). Two historical earthquakes that occurred near Banda Aceh was generated by Seulimeum Segment with M 6.5 in 1964 and Aceh Segment (M 6.0) in 1997. Besides, another felt earthquake occurred outside two segments in Bener Meriah 2013 (M 6.2) and Pidie Jaya 2016 (M 6.5) with strike-slip mechanism (Muksin et al., 2019; Simanjuntak et al., 2018, 2019; Qadariyah et al., 2018). Last, the earthquake in 2020 occurred with M 4.8 near Peukan Bada. BMKG reported the shakemap for this earthquake around 3-4 MMI.

From several earthquake reports released, many people in Banda Aceh felt a very strong ground motion from near and far-field. For example, the 2013 Benera Meriah earthquake with IV-V MMI, the 2016 Pidie Jaya earthquake with the V-VI MMI, and the 2020 Sabang earthquake with III-IV MMI (BMKG, 2020). The shaking reports were supported by the geological condition of Banda Aceh which stands on a basin with alluvial sediment (Qh) as shown in Figure 2.
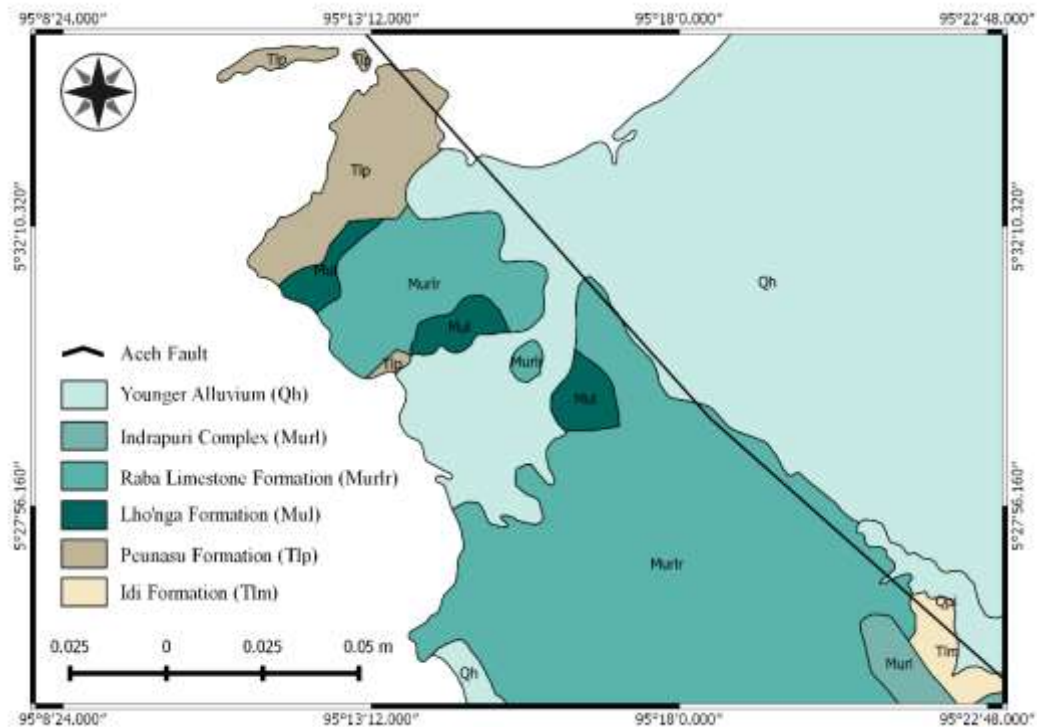
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Figure 2. Geology map of the study area (Modified from Bennet, J.D. et al., 1981).

The alluvial sediment (Qh) has been formed since the Cenozoic by the local and regional tectonic process (Bennet et al., 1981). The alluvial (Qh) is mostly located in the northernmost part of Banda Aceh especially in Peukan Bada and as the upper layer of Banda Aceh basin. Meanwhile, the limestone rock (Murl) is located near the southern part of Banda Aceh (Rusydy et al., 2020; Asrillah et al., 2020).

Data and Method

Microtremor measurements were carried out in Peukan Bada based on two reasons, first is located near active segments and densely populated. A total of 20 locations were measured with a short period seismometer and recorded with a sampling rate per second of 100 sps in 45 minutes as shown in figure 3.

Figure 3. Survey location in subdistrict Darul Imarah and Peukan Bada with total site 20 points.

The recording may contain some noise from nature or machine activity that close to the instrument. Therefore, we manually checked by converting the waveform into spectrogram as shown in figure 4.
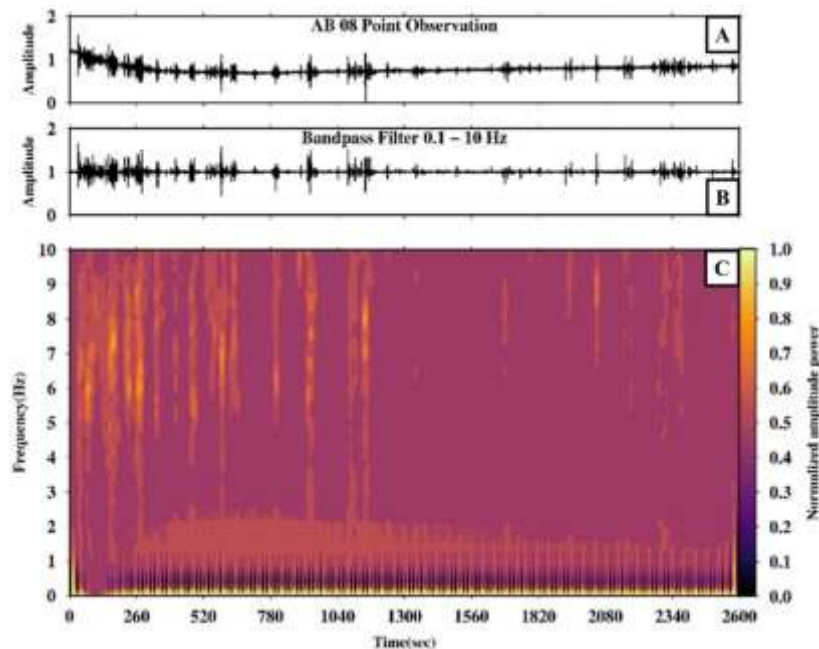

Figure 4. The seismic waveform was recorded at the observation point AB 08 (a), before and after the 0.1-10 Hz bandpass filter was carried out (b). From spectrogram, the recording has some noise that occurred when installation in 0-500 s with a frequency range of 4 - 10 (c).

The spectrogram is very useful to inform what filter range is fit for H/V analysis. From figure 4, the condition in the site of AB 08 is quietly low noise. Some noise was trapped when the first installation between 0 – 500 s with frequency > 5hz. Data analysis for seismic recording in figure 4 was performed by using the HVSR method that uses surface waves, namely Rayleigh.

Rong et al., (2017) compared H/V in rayleigh waves as shown in figure 5, and concluded that microtremor mostly affected by rayleigh waves. Besides, H/V spectrum peaks are obtained from rayleigh wave polarity analysis (Konno and Ohmachi, 1998; Stanko et al., 2016; Rong et al., 2017). H/V spectrum analysis is considered suitable for rayleigh wave type to conduct the realistic microseismic wave (Tarabusi et al., 2017; Nakamura, 2019).

Horizontal to Vertical Spectral Ratio (HVSR)

H/V ratio is a comparison of two wave components which results in a vulnerability value (Dal Moro, 2020). H/V method was developed by Nakamura (2019) by calculating the ratio of the fourier spectrum of the horizontal component to the vertical component microtremor signals (Martorana et al., 2018).

Stanko et al., (2016) separate the effect of the wave source on local geology, by normalizing the spectrum of the horizontal component with the vertical component at the same measuring point. The results of the observations show that the recording on stations located on the hard rock has a maximum value of the spectrum ratio of the H/V component with a value of 1.

While for stations located on soft rock, the maximum value undergoes amplification that is greater than 1. Based on this, a well-known analysis was formulated as a transfer function of microseismic HVSR (Tarabusi et al., 2017). The assumptions used in the Nakamura method are presented in figure 5.

Then, the time domain is transformed into the frequency domain with operation Fast Fourier Transform (FFT) so it can be known as a corner frequency to determine the upper and lower frequency limit. In the processing, Bandpass Butterworth filter is used to get a typical range microwave frequency (Bignardi, 2017).
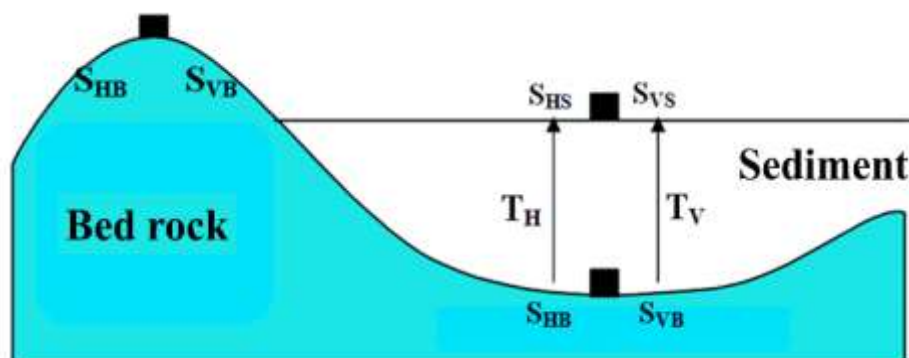

Figure 5. Basin models that contain fine sedimentary material (Modified Nakamura, 2019).

Site Effect (T_{SITE}) on the surface of the sediment layer, obtained by comparing the amplification factor of horizontal and vertical movements on the surface of sedimentary rocks.

$$T_{SITE} = \frac{T_H}{T_V} \quad\text{...(1)}$$

The magnitude of horizontal and vertical amplification factors ($T_{H, V}$) is the ratio of the horizontal spectrum of motion at ground level (S_{HS}) and the bottom of the ground (S_{HB}):

$$T_H = \frac{S_{HS}}{S_{HB}} \quad\text{.. (2)}$$

Nakamura's previous observations showed recordings on hard rock or bedrock stations, the maximum value of the H/V component spectrum ratio approaching the value 1. So that:

$$\frac{S_{HB}}{S_{VB}} \approx 1 \quad\text{or}\quad \frac{S_{HB}}{S_{VB}} = 1 \quad\text{...(3)}$$

Through equations (2) and (3) substituted into equation (1), we obtain:

$$T_{SITE} = \frac{\frac{S_{HS}}{S_{HB}}}{\frac{S_{VS}}{S_{VB}}} = \frac{S_{HS}}{S_{HB}} \times \frac{S_{VB}}{S_{VS}} \quad\text{...(4)}$$

By doing the opposite, equation (4) produces equality (5), namely:

$$T_{SITE} = HVSR = \frac{\sqrt{(S_{\,Utara-Selatan})^2 + (S_{\,Barat-Timur})^2}}{S_{\,VS}} \quad\text{.......................(5)}$$

The HVSR value is the peak of the spectrum at the dominant frequency at one measurement point. HVSR also calculate the amplification as the micro zonation parameter. The amplification factor is mostly influenced by the wave speed and rock density, if the wave speed is getting lower, the amplification will be larger.

Furthermore, the seismic index (K_g) can be calculated by dividing the square of the amplification by the dominant frequency value as follows:

$$Kg = \frac{A^2}{F} \quad\text{...(6)}$$

K_g value can be used as a microtremor parameter to identify soil weak regions, vulnerability level and calculating the damage possible in the area with high seismic activity (Gosar, 2007; Kang et al., 2020).

Result and Discussion

In this study, transient waves are obtained from anti-triggering by comparing Short Term Average (STA) and Long Term Average (LTA), and the values used are 0 and 30 s. Furthermore, smoothing is given to refining the data

patterns of each data component by the Konno-Ohmachi (1998) method. Then, the H/V spectral ratio is used to get the dominant parameter as shown in figure 6.
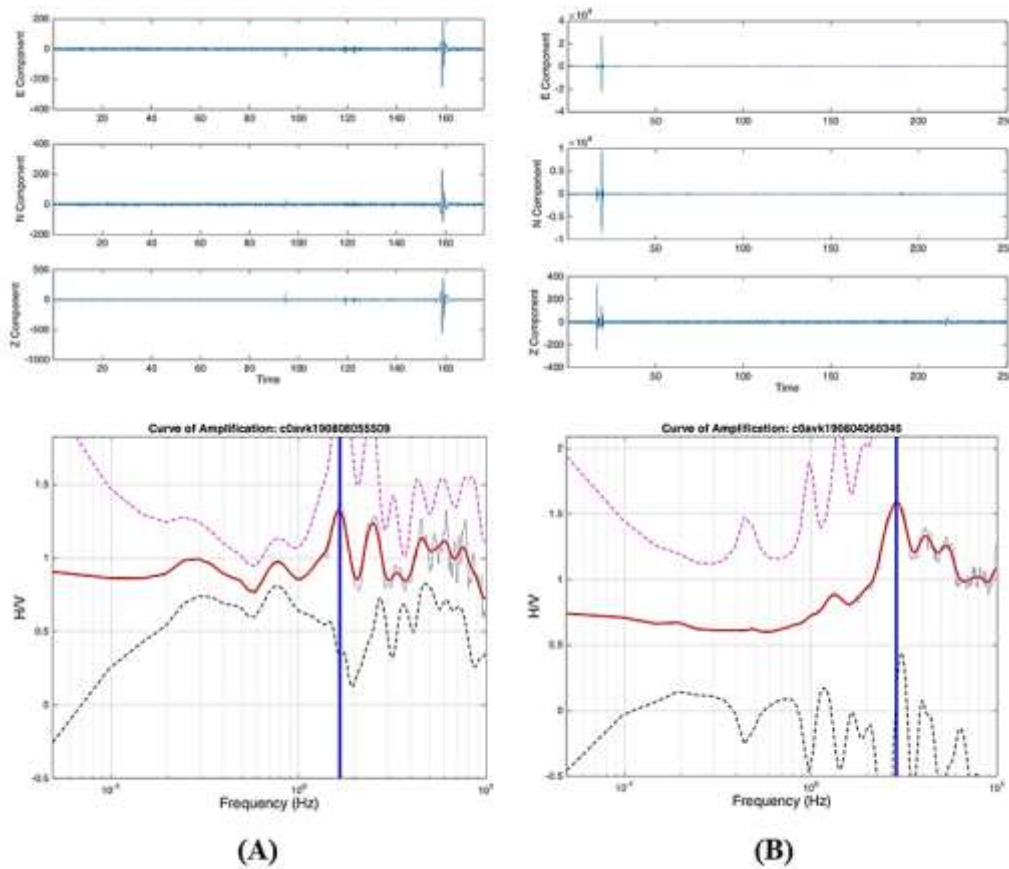

Figure 6. The example results from two points (AB 15 and AB 18) that contain H/V parameter in the frequency range and the seismic waveform recording.

Dominant parameter

Microtremor survey data at a predetermined point was analyzed using Geopsy. Based on the analysis results obtained dominant frequency and amplification which then calculated the value of seismic vulnerability (kg) in e.q (6). Furthermore, the results obtained based on these values can be calculated to get the value of the seismic vulnerability index (Kg) of Peukan Bada regions, as shown in Table 1.

Table 1. Result table of dominant frequency (F), period (T), amplification (A) and seismic index (Kg) in all site.

Site	Longitude	Latitude	F (Hz)	T (s)	A	Seismic Index (Kg)
AB 01	95.28005	5.53084	2.1201	0.47168	0.55851	0.147131
AB 02	95.27454	5.52623	2.5287	0.39546	0.7239	0.207233
AB 03	95.27074	5.51602	2.524	0.39620	0.5401	0.115531
AB 04	95.27898	5.52206	2.7653	0.36162	0.57506	0.119587
AB 05	95.28534	5.52817	1.5011	0.66618	1.7281	1.989427

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(www.jurnal.ar-raniry.ac.id/index.php/elkawnie)

DOI: 10.22373/ekw.v6i2.7886 **| 350**

AB 06	95.29086	5.52219	1.5673	0.63804	1.4547	1.350190
AB 07	95.28295	5.51906	3.5697	0.28014	0.2052	0.011796
AB 08	95.31145	5.51426	2.0764	0.48160	1.2910	0.801435
AB 09	95.29904	5.51612	2.7398	0.36499	0.7226	0.190580
AB 10	95.33632	5.50532	2.161	0.46275	0.971	0.436298
AB 11	95.31339	5.52046	2.539	0.39386	0.959	0.362222
AB 12	95.30551	5.50481	3.615	0.27663	0.1012	0.002822
AB 13	95.30123	5.50451	5.506	0.18162	0.1702	0.005249
AB 14	95.31984	5.49429	2.646	0.37793	0.998	0.376419
AB 15	95.3202	5.50781	1.014	0.98619	1.561	2.403078
AB 16	95.32961	5.49682	2.289	0.43687	1.243	0.674989
AB 17	95.33191	5.50979	2.581	0.38745	0.795	0.244876
AB 18	95.32777	5.52613	1.484	0.67385	1.865	2.343817
AB 19	95.33781	5.51391	2.809	0.35600	0.738	0.193892
AB 20	95.29011	5.51205	3.514	0.28458	0.261	0.019386

Soil Classification

Based on the dominant frequency values in Table 1, the classification and type of soil can be determined based on the model from Kanai and Tanaka (1961). The classification is very necessary to understand the local geological conditions of the study area (Khalili, 2019).

Classification is based on the dominant frequency values obtained from each measurement point. The dominant frequency obtained generally illustrates the condition of the soil which is quite soft with its constituents namely alluvium and mud. Land classification data at the survey sites in the Peukan Bada areas are shown in the following Table 2:

Table 2. Soil Types based on Kanai and Tanaka (1961) Site Classification at Peukan Bada.

Class	F_0 range (Hz)	Point	$F_{0\ (Hz)}$	Site Type
I	> 3 Hz	AB 07	3.5697	Tertiary Stone (Hard Rock)
		AB 12	3.615	
		AB 13	5.506	
		AB 21	3.514	
II	> 2.5 Hz	AB 19	2.809	Limestone (Hard Clay)
		AB 02	2.5287	
		AB 03	2.524	
		AB 04	2.7653	
		AB 09	2.7398	
III	2.0 – 2.5 Hz	AB 08	2.0764	Alluvial Stone (buff formation)
		AB 10	2.161	
		AB 11	2.539	

Elkawnie: Journal of Islamic Science and Technology Vol. 6, No. 2, December 2020
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		AB 14	2.646	
		AB 16	2.289	
		AB 17	2.581	
		AB 01	2.1201	
IV	< 2.0 Hz	AB 15	1.014	Sedimentary rock (sediment / mud)
		AB 18	1.484	
		AB 05	1.500	
		AB 06	1.5673	

Map-Based on the HVSR Method

Based on the analysis results in Table 1 and 2, we make an interpolation to interpret and see the differences in spatial conditions and to get a clear area that has some dominant parameter namely dominant frequency map, dominant period map, amplification map and seismic vulnerability map as shown in figure 6.
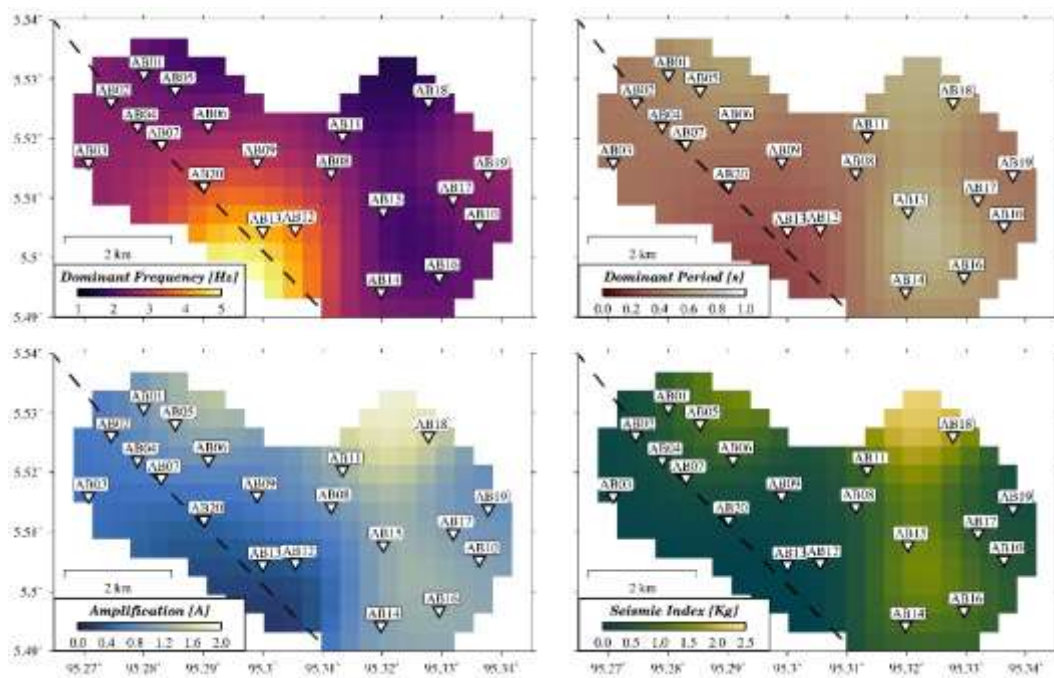

Figure 6. Map of dominant parameters; dominant frequency (f_0) and dominant period (T_0). Dominant parameters are needed in identifying conditions and land vulnerability for infrastructure purposes. Map of vulnerability index parameters consisting of amplification (A) and seismicity index (K_g).

From figure 6, low dominant frequency ($f_0 < 1.0$ Hz) can be found in the site point AB 01, 05, 06, 11, 08, 15, 14, 16, 10, 17 and 18. This area also has a high amplification factor (A > 1). Besides, the area with low frequency is dominated by sedimentary soil composed of mud and young alluvium (Qh). The alluvium is the main sediment in the upper layer of the Banda Aceh basin (Rusydy et al., 2020; Asrillah et al., 2020; Yusran et al., 2020). Some areas above the

Banda Aceh basin generally have a high vulnerability because of the soft sediment that can amplify the surface wave and ground shaking.

Furthermore, several locations in the western part of Aceh segment have relatively compact rock structures. The geological conditions show if the western part is dominated by limestone rock and alluvial with a hard stone. The results show AB 02, 04, 07, 20, 13, 12, and 03 is dominated by moderate-high frequency ($f_0 > 2.5$ Hz). This area is close to the Aceh segment and the amplification is less than the eastern part of the study area.

Besides, this area can be classified as the tertiary and limestone in the class of I and II. The amplification in this area has small value because of a compactness structure. The dominant period (T_0) in figure 6 is a reversal of the dominant frequency value ($1/f_0$). The dominant period is in the range of 0 - 0.5 seconds. The dominant period is a measure of the vulnerability of a building when it is crossed by surface waves (rayleigh and love). The range of 0 - 0.5 seconds can be categorized as the period range for local earthquakes.

This value is a consideration in establishing multilevel buildings because Peukan Bada is located very close to the active segment of Aceh which is a source of local earthquakes. High soil amplification values are at points AB18 and AB16. Amplification gives the strengthening effect of the earthquake waves when the material is not compacted. From Figure 6, the highest amplification value is evenly distributed at the measurement point in the mud and alluvial sedimentation area which is the compiler material for the Banda Aceh basin. Furthermore, we compare all parameters that have a linear relationship as shown in figure 7.
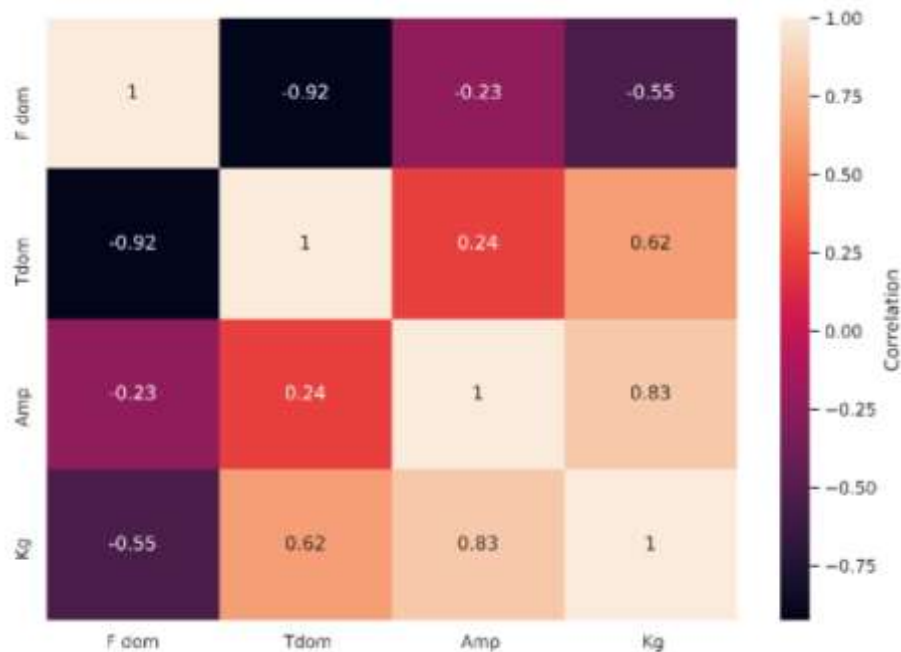

Figure 7. The relationship and the correlation value of each dominant parameter in the matrix heatmap.

The result of linear amplification is also the highest seismic vulnerability index in the Banda Aceh basin. These results are a good illustration and input in supporting mitigation in Banda Aceh. A high vulnerability index in the basin area is common because of the dominance of the material that consists of sediment.

In Figure 7, the correlation index of each parameter is modelled in the heatmap matrix. The matrix provides the relationship conditions for each dominant parameter obtained. A negative correlation index describes two (or more) parameters in opposite directions. This indicates that an increase in one variable will be followed by a decrease in other variables. The relationship of each parameter shows an interrelated and complementary result.

The highest negative correlation index exists in the relationship f_0 and T_0 because both are calculated by reversing each other. Meanwhile, the highest index is in the relation of amplification (A) and seismic vulnerability (Kg). Both are parameters that linearly related because of proportional to each other or influence each other to obtain the appropriate value.

Conclusion

Peukan Bada is dominated by alluvial material and mud sediments. From all site results, the percentage obtained is 65% of the geological conditions are quite vulnerable to earthquakes because the compiler material is soft or not compact. The high-frequency values (f0 > 2.5 Hz) and low dominant periods (T > 0.5 s) are influenced by compactness material from hard soil and rock structure that close to the Aceh segments. The level of vulnerability (K_g > 1.0) obtained in the Peukan Bada is quite high and proportional to the soil type that can amplify the seismic waveform. The high vulnerability was obtained due to the geological factor of the existence of Banda Aceh basin. This factor is very appropriate to be input and part in planning for disaster mitigation and the appropriate type of building.

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