Seismic Hazard Microzonation of Bengkulu City, Indonesia

Lindung Zalbuin Mase (lmase@unib.ac.id)
Universitas Bengkulu

Nanang Sugianto
Universitas Bengkulu

Refrizon Refrizon
Universitas Bengkulu

Research

Keywords: Earthquakes, Shear Wave Velocity, Microtremor, Site Class, Bengkulu

DOI: https://doi.org/10.21203/rs.3.rs-42761/v2

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License
Abstract

It has been known that Bengkulu City (Indonesia) is vulnerable to undergo seismic damage. This study is initiated by measuring horizontal to vertical spectral ratio ($H/V$) to sites in Bengkulu City using microtremor. The inversion analysis is performed to generate shear wave velocity profile. Hundreds of sites are investigated in this study. The results show that observed $H/V$ is consistent with the theoretical $H/V$. National Earthquake Hazard Reduction Program code is adopted to classify the site class. The results also exhibit that Bengkulu City is dominated by Site Classes C and D. In general, this study could lead local government to reconsider seismic hazard mitigation for spatial plan.

Introduction

Bengkulu City is a capital city of Bengkulu Province, Indonesia. This city is located on the western part of Sumatera Island, which is bordered with Indian Ocean. Recently, the city has been promoted as one of tourist destinations in Indonesia. However, earthquakes threats have been identified as the main issue in Bengkulu City since last two decades. Mase (2017) reported that at least two major earthquakes had occurred within last two decades. The first strong earthquake happened on June 4, 2019, with $M_w$ 7.9 (the Bengkulu-Enggano Earthquake), while the second strong earthquake happened on September 12, 2007 with $M_w$ 8.6 (the Bengkulu-Mentawai Earthquake) (Figure 1). Misliniyati et al. (2018) noted that those devastating earthquakes had triggered huge damage to structural buildings and lifelines facilities. Those earthquakes also triggered liquefactions along coastal area of Bengkulu City (Mase, 2017). Learning from past earthquake events, the effort to escalate seismic hazard mitigation in Bengkulu City should be prioritised.

Studies of earthquake hazard in Bengkulu City had been performed by several local researchers. Mase (2017) performed analysis of liquefaction potential along coastal area of Bengkulu Province based on site investigation data and geophysical measurements. Mase (2017) highlighted that liquefaction could happen along coastal area of Bengkulu City, especially during the Bengkulu-Mentawai Earthquake. Mase (2018) performed a reliability study of designed spectral acceleration for structural buildings in Bengkulu city and found that spectral acceleration resulted during seismic wave propagation had exceeded the designed spectral acceleration. Mase (2018) suggested that it is important to propose the updated design. Mase (2018) also recommended that seismic amplification effect should be considered in composing the updated designed spectral acceleration. Farid and Hadi (2018) investigated ground shear strain ($g$) in Bengkulu City based on microtremor measurements. Farid and Hadi (2018) found that geological condition of Bengkulu City is dominated by alluvium materials. Those materials are composed of sandy soils, which are very sensitive to undergo liquefaction during earthquakes. In general, those previous studies had presented preliminary investigation on soil damage during earthquakes in Bengkulu City. However, seismic microzonation study related to local site condition has not performed yet.

Subsurface geophysical measurements included two major methods, which are widely known as passive and active methods. The implementation of passive method using microtremor is more preferable.
Workability, low cost, and accuracy aspects are some reasons why this method is more chosen. Several researchers, such as Gosar (2010), El-Hady et al. (2012), and Mase et al. (2020) had performed microtremor measurements for site investigation. Generally, those previous studies emphasised on depicting site characteristic based on time-averaged shear wave velocity for first 30 m depth ($V_{s30}$). Mase et al. (2020) suggested that $V_{s30}$ is the important parameter to describe seismic vulnerability in an area. It is therefore very useful to be implemented in the area with high seismic intensity, such as Bengkulu City, Indonesia (Mase, 2019).

In line with the previous studies, the investigation to local site condition and seismic hazard mitigation in Bengkulu City is still becoming the issue, which is still rarely presented. This paper presents a seismic microzonation study. The microtremor measurements and site investigations were performed at hundreds of sites in Bengkulu City. The horizontal to vertical spectral ratio ($H/V$) is obtained from measurement. Furthermore, the inversion analysis is performed to generate shear wave velocity ($V_s$) profile. $V_s$ profile is then analysed to determine $V_{s30}$, which is used to classify site condition. This study also presents seismic hazard map and $V_{s30}$ map which can contribute to the seismic hazard mitigation for Bengkulu City. In general, the results could provide information about seismic vulnerability in Bengkulu City, which can be used as a reference in developing the city on the basis of seismic hazard mitigation.

**Seismotectonic Setting**

Bengkulu Province has been known as an area, which has a high seismic intensity (Mase, 2017). In Figure 1, seismotectonic setting of Bengkulu Province is presented. There are three active tectonic settings which frequently triggered earthquakes in Bengkulu Province and its surrounding areas. The first earthquake source is Sumatra Subduction. This zone is the plate boundary between the Eurasian Plate and the Indo-Australia Plate. This subduction zone had triggered two major earthquakes in Bengkulu Province (the $M_w$ 7.9 Bengkulu-Enggano Earthquake in 2000 and the $M_w$ 8.6 Bengkulu-Mentawai Earthquake in 2007).

In Sumatra plain, a large fault system crossing Sumatra Island exists. This zone is known as Sumatra Fault System (Mase, 2020). This fault system is categorised as slip strike fault. Sieh and Natawidjaja (2000) mentioned that Sumatra Fault is situated between subduction zone in Southern Java and oblique subduction system in Sumatra. McCaffrey (2009) mentioned that this fault is associated with the oblique convergence between Indo-Australian Plate and Eurasian Plate. The earthquake history recorded that this fault had triggered both the $M_w$ 6.8 Liwa Earthquake and the $M_w$ 7.9 Alahan Panjang Earthquake in 1994 (Widiwijayanti et al., 1996 and Natawidjaja and Triyoso, 2007). Another active fault, which is known as Mentawai Fault System is located between Sumatra Subduction and west coast of Sumatra (Sieh and Natawidjaja, 2000). The Mentawai Fault system is also categorised as strike-slip fault zone. This fault had triggered a major earthquake, which was called as the $M_w$ 7.6 Padang Earthquake in 2009 (McCloskey et al. 2010).
Geological Condition

Figure 2 presents geologic map of Bengkulu City. Generally, alluvium terrace (Qat) sediment is dominant, especially along coastal area up to middle part of Bengkulu City. Qat is composed of sediment materials, such as sand, silt, clay, and gravel. Mase (2017) mentioned that during the Mw 8.6 Bengkulu-Mentawai Earthquake, liquefaction evidence had been found on sites dominated by Qat. The reef limestone (Ql) is also found on coastline parts. Shallow soil deposits composed of sandy soils were underlain by reef limestone in this formation. At the borders between Central Bengkulu Regency and Seluma Regency and at several northern parts of Bengkulu City, Bintunan formation (QTb) is found. This formation is composed of rock materials, such as polymictic conglomerate, breccia, reef limestone, tuffaceous claystone, and wood fossil. In the eastern part of Bengkulu City, which is bordered with Central Bengkulu Regency and Seluma Regency, Andesite (Tpan) formation is found. This area is high terrain area in Bengkulu City. Swamp deposit (Qs) is found in northern and western parts. This deposit consisted of sand, silt mud, clay and plant fossil. Alluvium (Qa) deposit is dominant in the middle part of Bengkulu City. Several materials, such as boulder, gravel, sand, silt, mud, and clay, are identified as the composing materials (Natural Disaster Agency of Bengkulu Province, 2018).

Mase et al. (2018b) had presented typical geological condition of Bengkulu City (Figure 3). Generally, typical subsoils in Bengkulu City are composed of three main materials, i.e. clayey soil, sandy soil, and rock. Clayey soils, such as organic clay (OH), high plasticity clay (CH), and silty clay (CM) are found at first two layers. These layers have cone resistance ($q_c$) of 2 to 30 kg/cm$^2$ and $V_s$ of 94 to 353 m/s. Furthermore, granular soils composed of silty sand (SM), poor-graded sand (SP), clayey sand (SC), and clayey gravels (GC) are found at third and fourth layers, with $q_c$ of 30 to 250 kg/cm$^2$ and $V_s$ of 200 to 614 m/s. The soft-rocks composed of sandstones are generally found below those sand layers, which has $q_c$ more than 250 kg/cm$^2$ and $V_s$ of 476 to 760 m/s.

Theory And Methodology

4.1 H/V Method

Several researchers, such as Lachet et al. (1996), Bard (2004), El-Hady et al. (2012), and Mase et al. (2020) had implemented microtremor measurement to observe local site condition. In its applicability, horizontal motion of microtremor, which is composed of shear waves is used as measurement assumption. Predominant period ($T_0$) and Horizontal to Vertical Spectral Ratio ($H/V$) are estimated based on horizontal motions spectra which reflect the transfer function at investigated site.

The use of $H/V$ method was firstly introduced by Kanai and Tanaka (1954) (popularised by Nakamura (1989)). This method is derived from spectral ratio of horizontal motion, which is transferred from microtremor measurement. Mase et al. (2020) mentioned that $H/V$ method is reliable to expect shear waves velocity at a site. Atakan (2009) explained that $H/V$ from earthquake shaking recorded on sediment surface to bedrock surface is generally consistent with $H/V$ from microtremor measurement.
Lachet and Bard (1994) suggested that $H/V$ method can be used to estimate predominant frequency. Lachet and Bard (1994) also mentioned that $H/V$ method can result in the expected estimation of site response of sediment soil deposits. $H/V$ is calculated by comparing Fourier Spectra between horizontal components and vertical component, as expressed in the following equation,

\[
\text{see equation 1 in the supplementary files section.}
\]

where, $H_{(EW)}$ and $H_{(NS)}$ are the Fourier amplitude spectra of horizontal in east-west and north-south directions, respectively, and $V$ is vertical spectra value.

Lachet et al. (1996), Koçkar and Akgün (2012), Mase (2019), and Mase et al. (2020) highlighted that $H/V$ Method is very useful in predicting local site condition. Spectral ratios obtained from $H/V$ method is relatively more stable than other raw noise spectra. Koçkar and Akgün (2012) mentioned that $f_0$'s well correlated to clear peak of $H/V$ or amplitude ($A_0$). However, noises caused by human activities, environmental settings, and other active vibration sources at surface could affect measurement quality. Therefore, measurement should be carefully performed to ensure the appropriate result. However, Bonnefoy-Claudet et al. (2006) stated that $H/V$ method is effective to predict predominant frequency ($f_0$) (simply predicted by $1/T_0$). Raptakis et al. (2005) explained that even though the limitation of $H/V$ has been recognised, the method is still widely used. SESAME (2004) compiled the criteria to determine the clear peak of $H/V$, which could help engineers to determine site condition for engineering practice (the detail can be found in SESAME (2004)).

In this study, a triaxial geophone-broad band seismometer called PASI Gemini is used to measure microtremor on each investigated site. The seismometer consisted of three components, i.e. east-west (EW), north-south (NS), and up-down (UD). The equipment is also applicable to measure strong and weak motions. The digitisers are let to warm up for 5 minutes before measurement. This treatment is expected to avoid problem of low frequency range and to obtain reliable data. Each measurement is performed with the duration of 30 minutes. Once the measurement is completed, noises from recorded data are removed and processed based on SESAME (2004) criteria. Results are then analysed to generate $H/V$ curve. Next, $H/V$ curve is analysed to generate $V_s$ profile. In this study, the inversion technique introduced by García-Jerez et al. (2016) is used. The inversion of $H/V$ is computed based on Monte Carlo sampling simulated annealing (García-Jerez et al., 2016).

The adopted model from García-Jerez et al. (2016) required several parameters for each layer. Those parameters are soil thickness, pressure wave velocity ($V_p$), shear wave velocity ($V_s$), soil density ($\rho$), and Poisson's ratio ($\nu$). The assumption of elastic half-space is adopted for the bottom layer. Furthermore, each parameter is ranged from minimum to maximum value, which is defined from a-priori knowledge of soil properties (Wathelet, 2008) in Monte Carlo Simulation. In this study, values of required parameters are taken from the information of typical soil layer in Bengkulu City. The shear wave velocity is derived from the correlation provided by Imai and Tonouchi (1982). $V_s$ may be also predicted from the elastic theory, which is related to Poisson's ratio and elastic modulus (Salencon, 2001). To predict $V_p$, ratios of
$V_p/V_s$ are also firstly assumed in the model (Tatham, 1982). Several researchers, such as Wathelet (2008), García-Jerez et al. (2016), Mase et al. (2020), and Mase (2019) stated that several parameters including $V_p$, $V_s$, and Poisson’s ratio could be categorised as the interdependent parameters. The Monte Carlo simulation is initiated with the starting guess model whose parameters are randomly selected within the ranges listed in Table 1. The velocity profiles and other parameters are calculated repeatedly until measured $H/V$ curve and calculated $H/V$ curve are consistent each other.

### 4.2 Site Classification

National Earthquake Hazard Reduction Provision (1998) introduced the criteria to classify local site condition. The criteria were derived based on time-averaged shear wave velocity for first 30 m depth ($V_{s30}$) as expressed in this following equation,

See equation 2 in the supplementary files.

In Equation 2, $d_i$ is thickness of each layer, $V_{si}$ is shear wave velocity of each layer, and $n$ is the number of layers for first 30 m depth. The criteria to determine site classification based on $V_{s30}$ are summarised in Table 2. Generally, the identification of site classification is very important in earthquake engineering practice. Likitlersuang et al. (2020) mentioned that the information of shear wave velocity for first 30 m depth is necessary to observe soil response during seismic wave propagation. In this study, the interpretations of site classification and shear wave velocity are elaborated.

### 4.3 Methodology

This study is systematically performed based on flow chart presented in Figure 4. This study is initiated by capturing geo-hazard issue in Bengkulu City. Several literatures related to earthquake aspect and geological condition of Bengkulu City were reviewed. Furthermore, data collection (cone penetration tests or CPT and microtremor records) was performed. CPT tests were addressed to obtain geological condition. CPTs were also used as a consideration in determining starting guess model. Microtremor measurement on each site was recorded by using PASI seismometer. Secondary data used in this study were geologic map of Bengkulu City, typical geological condition, and topography map. Geologic map and typical geological condition would help to understand subsoils in Bengkulu City. For access information to sites, topography map would be useful in this study. There are 183 microtremor points and 32 cone penetration test (CPT) points measured in this study. In addition, standard penetration tests (SPT) are performed at representative sites (P-1 to P-6 points in Figure 2).

After the data collection, the data analysis was conducted. At this stage, microtremor record on each site is processed to generate $H/V$ curve. To obtain the reliable $H/V$ curve, the results were examined by SESAME (2004) criteria. If $H/V$ curve was not fulfilled the criteria, measurement would be performed again. In this study, several $H/V$ curves representing each geological condition in Bengkulu City (Figure 2) were also elaborated.
Afterwards, inversion analysis was performed. In this study, the model adopted from García-Jerez et al. (2016) was used. The initial model referred to geological condition of Bengkulu City (Figure 3 and Table 1). The model would randomly seek the best model based on the ranges. From inversion analysis and measurement, several issues were discussed in this study. They are $H/V$ curve, peak $H/V (A_0)$, $f_0$ and the comparison of $V_s$ profile on each geological formation. Seismic microzonation map based on $V_{s30}$ range was also elaborated in this study. In general, this study could describe seismic hazard vulnerability in Bengkulu City.

**Results And Discussion**

5.1 Measurement Results

To obtain the description of geophysical characteristic in Bengkulu City, several $H/V$ curves (P-1 to P-6) which represent geological formation in Bengkulu City (Figure 2), are presented in Figure 5. All $H/V$ curves have been also fulfilled the criteria of SESAME (2004).

In Figure 5, several $H/V$ curves with sharp clear peak have been demonstrated by Figures 5b, 5c, and 5e that represent P-2, P-3, and P-5, respectively. Those sites are located at QTb, Qa, and QI, respectively. For P-2, $A_0$ is 6.8101 and $f_0$ is 6.0154 Hz. $A_0$ values for P-3 and P-5 are 4.5793 and 2.2962, respectively, whereas $f_0$ values for P-3 and P-5 are 7.5231 and 6.5885 Hz, respectively. A large $A_0$ indicates that there is a large impedance contrast between sediment and bedrock in a site. Meanwhile, a large $f_0$ means there is a thin sediment thickness in a site. It seems to be realistic, since P-3 and P-5 tends to have thin sediment thickness underlain by the bedrock. Materials such as sand, silt, mud and boulder are dominant at Qa. Those materials have certainly different characteristic, which are also possible to influence amplification. For P-2, the impedance contrast between sediment and bedrock is relatively smaller than P-3 and P-5 since $A_0$ is relatively smaller. The sediment thickness of P-2 is relatively thinner than P-3 and P-5 sites because of larger $f_0$.

The flattered $H/V$ curves are presented by P-1 and P-4, which represent Qs and Tpan. P-1 is located at swamp deposit dominated by sand, silt, mud, clay with plant remains. Those materials seem to be underlain by shallow bedrock. P-4 site is located at andesite formation which has a thin sediment thickness underlain by bedrock. For those sites, $A_0$ are about 2.0918 and 2.7859, respectively, whereas values of $f_0$ are 4.0152 and 4.501 Hz, respectively. Both parameters indicate that there is a medium contrast between rock and sediment in P-1 and P-4. The $H/V$ curves also show that $f_0$ values are smaller than P-2, P-3, and P-5. P-6 which represents alluvium deposit is composed of sand, silt, clay, and gravel. Both $A_0$ and $f_0$ values are 2.1518 and 4.0963 Hz, respectively. It indicates that impedance contrast between rock and sediment is relatively medium. Similar to other sites, thin sediment may be also found in this site since $f_0$ value is quite large.

5.2 Predominant frequency
In Figure 6, it can be seen that predominant frequency ranges are varied. There are five ranges representing distribution of predominant frequency. Those ranges can be grouped into high predominant frequency, medium predominant frequency, and low predominant frequency. Zone of high predominant frequency ($f_0 > 5$ Hz) can be found on several areas in Bengkulu City, especially in southern part, southeastern part and western part. Those areas are generally dominated by Qs, Qa, Qat, QTb, and Tpan. Gosar (2010) mentioned that a high $f_0$ indicates that a thin sediment thickness.

Zone of low predominant frequency ($f_0 < 3$ Hz) is found along southern part (some parts of coastal area) and northern part. Those areas are mostly dominated by Qat and QTb. The materials, such as sand, silt, clay, and sandstone are found in this region. Several researchers, such as Misliniyati et al. (2018) and Mase (2017) predicted that sand deposit along coastal area of Bengkulu City could be very vulnerable to undergo liquefaction. In terms of sediment thickness, a low predominant frequency indicates a thick sediment thickness. Zone of medium predominant frequency ($3 \leq f_0 \leq 5$ Hz) is concentrated in midplain of Bengkulu City. This area is generally dominated by Qa. Several sediment materials, such as sand and clay are found in this formation. Based on predominant frequency distribution, it can be predicted that sediment thickness at sites with medium predominant frequency is not much thicker than sediment thickness at sites with low predominant frequency. However, it may be thicker than sediment thickness at sites having high predominant frequency.

5.3 Amplitude ($A_0$) or Peak $H/V$

$A_0$ distribution is also divided into 5 categories, which can be grouped into low $A_0$, medium $A_0$, and high $A_0$. In general, medium $A_0$ ($3 \leq A_0 \leq 5$) is dominant. Based on geological condition, medium $A_0$ areas are dominated by Qa, Qat, and Tpan. Gosar (2010) mentioned that a larger $A_0$ means a high impedance contrast between sediment and rock surface. The impedance contrast is the difference ability between the sediment and rock surface to propagate the seismic wave. Several areas, such as southern and northern parts of Bengkulu City have low $A_0$ ($A_0 < 3$). Those areas are also dominated by Qa, Qat, Qtb, and Qs formations. In terms of impedance contrast, a low $A_0$ indicates a low impedance contrast between sediment and rock surface. Small parts on the coastline of Bengkulu City indicate high $A_0$ ($A_0 > 5$). This area is dominated by Qat. $A_0$ is also related to the ability of sediment layer to amplify seismic wave propagation. Several studies (Mase (2017); Misliniyati et al. (2018); Mase (2020)) had confirmed that sites along coastal area of Bengkulu City could amplify during the Bengkulu-Mentawai Earthquake in 2007. Generally, the results are consistent with previous studies.

5.4 $H/V$ comparison and $V_s$ profile

The comparison between measured $H/V$ and inversion $H/V$ is presented in Figure 8. Generally, for all representative sites, $H/V$ curves resulted from measurement and inversion are relatively consistent each other. However, measurement curves slightly underestimated inversion curves. This is due to the fact that
the contrast of velocity in predicted models is rather stronger than real ground condition (Souriau et al., 2011).

Furthermore, $V_s$ profile is generated from the best model resulted from inversion analysis (Figure 9). In general, $V_s$ profiles increase with depth up to 30 m depth on each investigated point. For first 30 m depth, $V_s$ profiles consist of 4 to 5 layers. For P-2, P-3, P-4, P-5, thin layers with small difference of shear wave velocity profile are found. It indicates that the layer could have similar soil resistance. In addition, those thin layers are probably dominated by OH and CH, especially for first 2 m depth. Figure 9 also shows that $V_{s30}$ values at representative sites are observed to vary from 307 to 409 m/s. Therefore, those sites can be categorised as Site Classes C and D. The results of inversion analysis are generally consistent with site investigation data (Figure 10). Representative sites have low $V_s$ and N values at shallow depth, indicating that there is sediment materials, such as soft soils (CH and OH). Another clayey soils called CM is also found at second layer that has a larger velocity value than first layer. The granular materials are composed of SM, SP, SC, SW, and GC in the third and fourth layers. Those materials are categorised as medium to dense sediments. The increase of $V_s$ and N values on those materials indicate the high density. At several representative sites, such as P-2 and P-3, layers of engineering bedrock are also found. The layers are composed of sandstones with $V_s$ and N values relatively larger than previous layers. Site investigation data of Bengkulu City are well correlated with $V_s$ profile obtained from inversion analysis.

### 5.5 $V_{s30}$ and Seismic Hazard Microzonation

Figure 10 presents the contour of $V_{s30}$ for Bengkulu City. In Figure 10, there are five ranges of $V_{s30}$, i.e. $V_{s30}$ of 180-240 m/s, $V_{s30}$ of 240 to 300 m/s, $V_{s30}$ of 300 to 360 m/s, $V_{s30}$ of 360 to 420 m/s, and $V_{s30}$ of 420 to 480 m/s. Several researchers, such as Thompson and Wald (2012), Cannon and Dutta (2015), and Silva et al. (2015) had also implemented the ranges to observe site characteristics at Taiwan, Alaska, and Portugal, respectively. In general, there are three dominant $V_{s30}$ zones in Bengkulu City. The first one is $V_{s30}$ of 360 to 420 m/s, which is centralised in the eastern part of Bengkulu City. The zone of $V_{s30}$ of 300 to 360 m/s is the second dominant range in Bengkulu City. This zone is generally concentrated in the western part of Bengkulu City. The last dominant $V_{s30}$ range is also concentrated along coastal area of Bengkulu City.

The description of seismic hazard microzonation is presented in Figure 11. It can be seen that Bengkulu City is dominated by Site Class D (red colour). The map presents that most coastal areas are identified to have low $V_{s30}$ values. $V_{s30}$ values in those areas are generally within the range of 180 m/s to 360 m/s, which fall into Site Class D. In terms of geological condition, Site Class D are dominated by sediment materials, such as sandy soils and soft clayey soils which have low soil resistances. Mase (2017) and Mase (2018) also explained that sediment materials with low soil resistances are very vulnerable to undergo seismic impact, such as liquefaction and ground amplification. Site Class C ($V_{s30}$ within the range of 360 to 760 m/s), which is indicated by yellow colour is found in the eastern part of Bengkulu City. Generally, the eastern part of Bengkulu City is dominated by Tpan. This formation is composed of
stiff materials. During the Bengkulu-Mentawai Earthquake, Mase (2017) and Misliniyati et al. (2018) reported that there was no significant damage found in the eastern part of Bengkulu City. It might be due to larger soil resistance existing in this area. Meanwhile, liquefaction, ground failure and structural damage were found massively along coastal area of Bengkulu City. Based on the finding, it can be concluded that areas of site class C are relatively safer from seismic impacts. Other areas with similar site classes with Bengkulu City, such as Tauranga (Pearse-Danker and Wotherspoon, 2016), Rawalpindi-Islamabad (Khan and Khan, 2018), Himalayan Region (Anbazhagan et al., 2019), and Western Saudi Arabia (Alamri et al., 2020) had been also studied. Based on those previous studies, Site Class C is mostly found on areas underlain by relatively shallow bedrock dominated by rock formation and old alluvium deposits, whereas Site Class D is commonly found on basin areas dominated by alluvium terrace sediment. In Bengkulu City, the shallow bedrock areas are generally found on the high-terrain area in the eastern part of Bengkulu City that is also dominated by rock and alluvium deposit. Different from Site Class C, Site Class D in Bengkulu City is concentrated on the coastal area and basin area (the western part of Bengkulu City), which are also dominated by alluvium terrace sediment. In line with the characteristic of composed materials in Site Classes C and D, it can be concluded that general condition of site class in Bengkulu City is generally consistent with previous studies.

Overall, parameters of $f_0$, $A_0$ and $V_{s30}$ are well correlated with geological condition in the study area. Misliniyati et al. (2018), Farid and Hadi (2018), and Farid and Mase (2020) mentioned that the updated spatial plan of Bengkulu City should consider seismic hazard microzonation. Strengthen on the mitigation effort is very important for Bengkulu City as one of vulnerable areas to earthquake. The geophysical interpretations, such as $V_{s30}$ and site classification maps can describe the potential impact of seismic hazard in Bengkulu City. Site classification map composed based on $V_{s30}$ could represent general vulnerability to seismic damage. Bengkulu City is being also now promoted as one of tourist areas in Indonesia. The development of infrastructures and facilities to support the goal would be significantly raising near future. However, seismic hazard of Bengkulu City has not totally understood by local engineers. Therefore, the information of seismic hazard mitigation could be used by local government to strengthen seismic mitigation effort in Bengkulu City. The results of this study would also contribute to recommend local engineers in designing buildings which prioritise on seismic hazard mitigation in Bengkulu City. The effort would be effective to minimise the damage during earthquakes in Bengkulu City.

**Conclusion**

This paper presents the seismic hazard microzonation of Bengkulu City, Indonesia using the Inversion $H/V$ of microtremor observations. Many sites are observed in this study. The inversion analysis using Monte Carlo simulation simulated annealing is performed to determine the best model of site condition. $A_0$, $f_0$ and $V_{s30}$ are presented to characterise local site condition.
The geophysical parameters of site, such as $f_0$ and $A_0$ are relatively consistent with general geological condition of Bengkulu City. $f_0$ values can be used to estimate sediment thickness in the study area. Generally, Bengkulu City is dominated by $Q_s$ and $Q_{at}$. The sediment thickness in the study area is relatively thin. From the information, it can be roughly estimated that bedrock surface in Bengkulu City may be located at shallow depth.

In Bengkulu City, most sites tend to have medium ($3 \leq A_0 \leq 5$). It indicates that there is a medium impedance contrast between rock surface and sediment. For Bengkulu City, these dominant zones are dominated by $Q_a$ and $Q_{at}$. Those formations are composed of sediment materials, such as clay and sand. During the Bengkulu-Mentawai earthquake, the magnification of peak ground acceleration in these dominant zones are relatively large. Generally, field observations are consistent with evidence reported in previous studies.

This study also focused on seismic hazard microzonation in Bengkulu City. Site Class D is found on middle part to western part, whereas Site Class C is found on eastern part. Site Class D tends to have a lower soil resistance. It indicates that seismic damage could be more serious. In general, Site Class D is located along coastal area of Bengkulu City, which is prospectively developed as tourist area in near future. Therefore, spatial plan on the basis of seismic hazard assessment should be carefully considered in Bengkulu City.

Overall, the implementation of geophysical survey to determine site characteristic is successfully performed in this study. The inversion technique to determine $V_s$ is reasonably performed. The results could provide a better understanding of seismic hazard mitigation in Bengkulu City. Finally, the results could give a recommendation to local government in updating the spatial plan in Bengkulu City. The framework implemented in this study can be used to investigate site characteristics in other areas.

**Declarations**

1. **Available Data and Materials**

All the datasets that have been used and analysed during the current study is available from the corresponding author on reasonable request.

2. **Competing Interest**

I have declare that there is no any competing interests

3. **Funding**

It is not applicable in this case

4. **Authors’ Contribution**
5. Lindung Zalbuin Mase: Conceptualisation, Software, Validation, Formal analysis, Data Analysis, Visualization, Writing-Original draft- review-editing, Mapping, Project Administration.

6. Nanang Sugianto: Conceptualization, Methodology, Writing - original draft.

7. Refrizon: Conceptualization, Methodology, Writing - original draft.

8. Acknowledgement

This research was supported by Competitive Research Scheme from University of Bengkulu No. 2357/UN30.15/LT/2018. Authors would like to thank Soil Mechanics Laboratory and Geophysics Laboratory, University of Bengkulu for experiments and site investigations performed in this study.

6. Author Details

7. Lindung Zalbuin Mase: Assistant Professor, Department of Civil Engineering, University of Bengkulu, Bengkulu, Bengkulu, Indonesia

8. Nanang Sugianto: Research Assistant, Department of Geophysics, University of Bengkulu, Bengkulu, Indonesia

9. Refrizon: Associate Professor, Department of Geophysics, University of Bengkulu, Bengkulu, Indonesia

**Abbreviations**

H/V   : horizontal to vertical spectral ratio

$V_s$  : shear wave velocity

$V_{s30}$  : time-averaged shear wave velocity for first 30 m depth

Qat   : alluvium terrace

QI    : reef limestone

QTb   : bintunun formation

Tpan  : andesite formation

Qs    : swamp deposit

Qa    : alluvium deposit

OH    : organic clay

CH    : high plasticity clay

CM    : silty clay
$q_c$ : cone resistance
SM : silty sand
SP : poor-graded sand
SC : clayey sand
GC : clayey gravel
$T_0$ : predominant period

$H_{(EW)}$ : Fourier amplitude spectra of horizontal in east-west direction

$H_{(NS)}$ : Fourier amplitude spectra of horizontal in north-south directions,

$V$ : Fourier amplitude spectra of vertical

$f_0$ : predominant frequency

$A_0$ : peak of $H/V$ or amplitude

EW : east-west
NS : north-south
UD : up-down

$V_p$ : pressure wave velocity

$V_s$ : shear wave velocity

$r$ : soil density

$n$ : Poisson's ratio

$V_{si}$ : shear wave velocity of each layer

d$_i$ : thickness of each layer

$n$ : number of layers for first 30 m depth

CPT : cone penetration test

SPT : standard penetration test

N : the number of blows of SPT test for 1 ft penetration
References

Alamri, A. M., Bankher, A., Abdelrahman, K., El-Hadidy, M., & Zahran, H. (2020). Soil site characterization of Rabigh city, western Saudi Arabia coastal plain, using HVSR and HVSR inversion techniques. Arab J Geosci 13(2): 1-16. DOI:10.1007/s12517-019-5027-3

Anbazhagan, P., Srilakshmi, K. N., Bajaj, K., Moustafa, S. S., Al-Ari, N. S. (2019). Determination of seismic site classification of seismic recording stations in the Himalayan region using HVSR method. Soil Dyn Earthq Eng 116: 304-316. DOI: 10.1016/j.soildyn.2018.10.023

Atakan K (2009) The need for standardized approach for estimating the local site effects based on ambient noise recordings. In: Mucciarelli M, Herak M, Cassidy JF (Eds.), Proc of the NATO Advanced Research Workshop on Increasing Seismic Safety by Combining Engineering Technologies and Seismological Data. The NATO Science for Peace and Security Series-C: Environmental Security, XVIII, Dubrovnik, Croatia, 19–21 September: pp 3-15.

Bard PY (2004) The SESAME-FP5 project: an overview and main results. Proc of the 13th World Conference on Earthquake Engineering, Vancouver, Canada, 1–6 August.

Bonnefoy-Claudet S, Cornou C, Bard PY, Cotton F, Moczo P, Kristek J, Fah D (2006) H/Vratio: a tool for site effects evaluation. Results from 1-D noise simulations. Geophys J Int 167(2): 827–837. DOI: 10.1111/j.1365-246X.2006.03154.x.

Cannon EC, Dutta U (2015) Evaluating Topographically-Derived $V_{s30}$Values for Seismic Site Class Characterization in Anchorage, Alaska, USA. Proc of the 6th International Conference on Earthquake Geotechnical Engineering, 2-4 November, Christchurch, New Zealand.

El-Hady S, Fergany EAA, Othman A, Mohamed GEA (2012) Seismic microzonation of Marsa Alam, Egypt using inversion HVSR of microtremor observations. J Seismol 16(1): 55-66. DOI: 10.1007/s10950-011-9249-4

Farid M, Hadi Al (2018) Measurement of Shear Strain in Map Liquefaction Area for Earthquake Mitigation in Bengkulu City. Telkomnika 16(4): 1597-1606. DOI: 10.12928/TELOMNIKA.v16i4.8043

Farid M, Mase LZ (2020) Implementation of seismic hazard mitigation on the basis of ground shear strain indicator for spatial plan of Bengkulu City, Indonesia. Int J Geomate 18(69):199–207. DOI: 10.21660/2020.69.24759

García-Jerez A, Piña-Flores J, Sánchez-Sesma FJ, Luzón F, Perton M (2016) A computer code for forward computation and inversion of the H/V spectral ratio under the diffuse field assumption. Comp Geosci 97(1): 67–78. DOI: 10.1016/j.cageo.2016.06.016.
Gosar A (2010) Site effects and soil-structure resonance study in the Kobarid basin (NW Slovenia) using microtremors. Nat Hazards Earth Sys Sci 10(4): 761-772. DOI: 10.5194/nhess-10-761-2010.

Imai T, Tonouchi K (1982) Correlation of N-value with S-wave velocity. Proc. of 2nd European Symposium on Penetration Testing, 67-72, Amsterdam, Netherland, May 24-27.

Kanai K, Tanaka T (1954) Measurement of the microtremor. Bull Earthq Res Ins 32(1): 199–209.

Khan, S., & Khan, M. A. (2018). Seismic Microzonation of Islamabad–Rawalpindi Metropolitan Area, Pakistan. Pure Appl. Geophys 175(1): 149-164. DOI: 10.1007/s00024-017-1674-z

Koçkar MK, Akgün H (2012) Evaluation of the site effects of the Ankara basin, Turkey. J Applied Geophys 83(1): 120–134. DOI: 10.1016/j.jappgeo.2012.05.007.

Lachet C, Bard PY (1994) Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. J Phys Earth 42(5): 377-397.

Lachet C, Hatzfeld D, Bard PY, Theodulidis N, Papaioannou C, and Savvaidis A. (1996) Site effects and microzonation in the city of Thessaloniki (Greece) comparison of different approaches. Bull Seismol Soc America 86(6): 1692-1703.

Likitlersuang, S., Plengsiri, P., Mase, L. Z., & Tanapalungkorn, W. (2020). Influence of spatial variability of ground on seismic response analysis: a case study of Bangkok subsoils. Bull Eng Geol Environ 79(1): 39-51.

Mase LZ (2017) Liquefaction potential analysis along coastal area of Bengkulu Province due to the 2007 Ms 8.6 Bengkulu Earthquake. J Eng and Technol Sci 49(6): 721-736. DOI: 10.5614%2Fj.eng.technol.sci.2017.49.6.2.

Mase LZ (2018) Reliability study of spectral acceleration designs against earthquakes in Bengkulu City, Indonesia. Int J Technol 9(5): 910-924. DOI: 10.14716/ijtech.v9i5.621.

Mase LZ (2019) Seismic Vulnerability Maps of Ratu Agung District, Bengkulu City, Indonesia. Civil Eng Dimens 21(2): 97-106. DOI: 10.9744/ced.21.2.97-106.

Mase LZ (2020) Seismic Hazard Vulnerability of Bengkulu City, Indonesia, Based on Deterministic Seismic Hazard Analysis. Geotech Geol Eng 38: 5433–5455. DOI: 10.1007/s10706-020-01375-6

Mase LZ, Likitlersuang S, Tobita T, Chaiprakaikeow S, Soralump S (2020) Local site investigation of liquefied soils caused by earthquake in Northern Thailand. J Earthq Eng 24(7): 1181-1204. DOI:10.1080/13632469.2018.1469441.

Mase LZ, Sugianto N, Refrizon (2018b) Shear Wave Velocity Mapping for Spatial Plan of Bengkulu City. Report of Competitive Reserch No. 2357/UN30.15/LT/2018, University of Bengkulu, Bengkulu, Indonesia.
McCaffrey R (2009) The tectonic framework of the Sumatran subduction zone. Annu Rev Earth Planet Sci 37:345-366. DOI:10.1146/annurev.earth.031208.100212.

McCloskey J, Lange D, Tilmann F, Nalbant SS, Bell AF, Natawidjaja DH, Rietbrock A (2010) “The september 2009 padang earthquake. Nat. Geosci 3(2): 70-71. DOI:10.1038/ngeo753.

Misliniyati R, Mase LZ, Syahbana AJ, Soebowo E (2018) Seismic hazard mitigation for Bengkulu Coastal area based on site class analysis. IOP Conference Series: Earth and Environmental Science 212 (1), 012004. DOI:10.1088/1755-1315/212/1/012004.

Nakamura Y (1989) A method for dynamic characteristic estimation of subsurface using microtremor on ground surface. Quarterly Report of Railway Technical Research 30(1): 25–53.

Natawidjaja DH, Triyoso W (2007) The Sumatran fault zone—from source to hazard. J Earthq Tsunami 1(1): 21-47. DOI:10.1142/S1793431107000031.

National Earthquake Hazards Reduction Program (1998) Recommended Provisions for Seismic Regulation for New Buildings and Other Structures: Part 1-Provisions and Part 2- Commentary. FEMA 302, Texas, USA.

Natural Disaster Agency of Bengkulu Province (2018) Geological map of Bengkulu City, Indonesia. Natural Disaster Agency of Bengkulu Province, Bengkulu, Indonesia.

Pearse-Danker, E., & Wotherspoon, L. (2018). Site subsoil class determinations in Tauranga. NZ Geomechanic News, 62-71.

Raptakis DG, Manakou MV, Chavez-Garcia FJ, Makra KA, Pitilakis KD (2005) 3D configuration of mygdonian basin and preliminary estimate of its site response. Soil Dyn Earthq Eng 25(1): 871–887. DOI:10.1016/j.soildyn.2005.05.005.

Salencon J (2001) Handbook of Continuum Mechanics: General Concepts, Thermoelasticity. Springer Science and Business Media, Berlin, Germany.

SESAME (2004) Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation. http://sesame-fp5.obs.ujf-grenoble.fr/Delivrables/Del-D23HV_User_Guidelines.pdf. Accessed 28 September 2019.

Sieh K, Natawidjaja DH (2000) Neotectonics of the Sumatran fault, Indonesia. J Geophys Research: Solid Earth 105(B12): 28295-28326. DOI:10.1029/2000JB900120.

Silva V, Crowley H, Varum H, Pinho R (2015). Seismic risk assessment for mainland Portugal. Bull Earthq Eng 13(2): 429-457. DOI:10.1007/s10518-014-9630-0.
Souriau A, Chaljub E, Cornou C, Margerin L, Calvet M, Maury M, Wathelet M, Grimaud F, Ponsolles C, Pequegnat C, Langlais M, Guéguen P (2011) Multimethod characterization of the French-Pyrenean valley of Bagnères-de-Bigorre for seismic-hazard evaluation: observations and models. Bull Seismo Soc America 101(4), 1912–1937. DOI:10.1785/0120100293.

Tatham TH (1982) Vp/Vs and lithology. Geophysics 47(3): 336–344.

Thompson EM, Wald DJ (2012). Developing $V_{S30}$ site-condition maps by combining observations with geologic and topographic constraints. Proc of the 15th World Conference on Earthquake Engineering, 24-28 September, Lisbon, Portugal.

Wathelet M (2008) An improved neighbourhood algorithm: parameter conditions and dynamic scaling. Geophys. Res. Lett 35(1): 1–5. DOI:10.1029/2008GL033256.

Widiwijayanti C, Déverchère J, Louat R, Sébrier M, Harjono H, Diament M, Hidayat D (1996) Aftershock sequence of the 1994, Mw 6.8, Liwa earthquake (Indonesia): Seismic rupture process in a volcanic arc,” Geophys. Res. Lett 23(21): 3051-3054. DOI:10.1029/96GL02048.

### Tables

#### Table 1. Range values of initial parameters for H/V inversion

| Layer | Soil Type | Thickness | $V_s$ [m/s] | $V_p$ [m/s] | Density [kg/cm$^3$] | Poisson Ratio [n] |
|-------|-----------|-----------|------------|------------|-------------------|------------------|
| 1     | OH/CH     | 1-20      | 90-270     | 125-375    | 1800-2000         | 0.400-0.495      |
| 2     | CM        | 1-20      | 160-350    | 240-525    | 1800-2000         | 0.400-0.495      |
| 3     | SM, SP, SC | 1-20      | 200-500    | 300-750    | 1800-2000         | 0.200-0.400      |
| 4     | SW, SC, GC | 1-20      | 400-600    | 600-900    | 1800-2000         | 0.200-0.400      |
| Half-space Sandstone | ~ | 500-760 | 750-1140 | 2000-2200 | 0.100-0.300 |

Remarks: OH = organic clay, CH = high plasticity clay, CM= silty clay, SM = silty sand, SP = poor-graded sand, SC = clayey sand, SW = well-graded sand, GC = clayey gravel

#### Table 2. Site classification based on $V_{S30}$ (National Earthquake Hazard Reduction Provision, 1998)
| NEHRP Site Class | General Description                                      | Range of $V_{s30}$ [m/s] |
|------------------|----------------------------------------------------------|-------------------------|
| A                | Hard Rock                                                | $V_{s30} > 1500$        |
| B                | Rock                                                     | $760 \leq V_{s30} \leq 1500$ |
| C                | Very Dense Soil and Soft Rock                            | $360 \leq V_{s30} \leq 760$ |
| D                | Stiff Soil [$15 \leq N \leq 50$ or $50 \text{ kPa} \leq N \leq 100 \text{ kPa}$] | $180 \leq V_{s30} \leq 360$ |
| E                | Soil or any profile with more than 3 soft clay defiled as soil with PI $> 20$, $w \geq 40\%$, and $s_u < 25 \text{ kPa}$ | $V_{s30} < 180$ |
| F                | Soils requiring site-specific evaluation                 | -                       |

Remarks: $N =$ SPT value [blows/ft], $s_u =$ undrained shear strength, PI = plasticity index, $w =$ water content

**Figures**
Figure 1

Seismotectonic settings of Bengkulu Province, Indonesia and the epicentres of major earthquake on Bengkulu Province
Figure 2

Geologic map of Bengkulu City (modified from Natural Disaster Agency of Bengkulu Province, 2018)
Figure 3

Typical subsoils condition in Bengkulu City (Mase et al., 2018)

- **OH/CH**
  - Thickness = 1 to 3 m
  - $\gamma = 17$ to $18$ kN/m$^3$
  - $q_c = 2$ to $10$ kg/cm$^2$
  - $f_c = 0.08$ to $0.68$ kg/cm$^2$
  - $V_s = 94$ to $241$ m/s

- **CM**
  - Thickness = 1 to 7 m
  - $\gamma = 17$ to $18$ kN/m$^3$
  - $q_c = 10$ to $30$ kg/cm$^2$
  - $f_c = 0.2$ to $2.05$ kg/cm$^2$
  - $V_s = 165$ to $353$ m/s

- **SM, SP, SC**
  - Thickness = 1 to 15 m
  - $\gamma = 18$ to $21$ kN/m$^3$
  - $q_c = 30$ to $60$ kg/cm$^2$
  - $f_c = 0.5$ to $5.45$ kg/cm$^2$
  - $V_s = 200$ to $466$ m/s

- **SW, SC, GC**
  - Thickness = 1 to 20 m
  - $\gamma = 19$ to $22$ kN/m$^3$
  - $q_c = 80$ to $250$ kg/cm$^2$
  - $f_c = 3.53$ to $17.16$ kg/cm$^2$
  - $V_s = 408$ to $614$ m/s

- **Sandstone**
  - Thickness = not yet estimated
  - $\gamma$ more than $22$ kN/m$^3$
  - $q_c$ more than $250$ kg/cm$^2$
  - $f_c = 7.35$ to $52.17$ kg/cm$^2$
  - $V_s = 476$ to $760$ m/s
Figure 4

Research framework
Figure 5

HV curves at (a) P-1 (b) P-2 (c) P-3 (d) P-4 (e) P-5 and (f) P-6
Figure 6

Distribution of f0 in the study area
Figure 7

Distribution of amplitude (peak H/V) in the study area
Figure 8

Comparison between H/V measured and H/V Inversion
Figure 9

Shear wave velocity (Vs) profile up to 30 m depth for (a) P-1, (b) P-2, (c) P-3, (d) P-4, (e) P-5, and (f) P-6
Figure 10

Vs30 map for Bengkulu City
Figure 11

Seismic microzonation map of Bengkulu City