Lowland Technology International 2020; Volume 22(3): 001-013
International Association of Lowland Technology (IALT): ISSN 1344-9656

Research Paper

A comparative study of geophysical measurements to characterise the local site condition of Bengkulu City, Indonesia

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ARTICLE INFORMATION

Article history:

Received: 03 December, 2019
Received in revised form: 14 April, 2020
Accepted: 22 August, 2020
Publish on: 06 December, 2020

Keywords:

Major earthquakes
Surface waves
Ambient noise of microtremor
Shear wave velocity
Local site condition
Bengkulu City

ABSTRACT

Bengkulu City is one of the vulnerable areas to undergo earthquakes in Indonesia. Two major earthquakes happened in 2000 and 2007 had appeared the issue that the site condition played the important role in determining the seismic effect in Bengkulu City. However, the detail understanding of local site condition including the parameter to measure it, is still not fully achieved. This paper presents a comparative study of geophysical measurement to characterise local site condition in Bengkulu City. The geophysical surveys using Multichannel Analysis of Surface Wave (MASW) and Ambient Noise of Microtremor methods are performed to several sites in Bengkulu City. Furthermore, the inversion analysis to generate shear wave velocity (V_s) is performed. The comparisons to site class and time-averaged shear wave velocity for first 30 m depth (V_{s30}) are also compared. The results show that MASW results tend to be more conservative than Microtremor results. However, both measurements show the similar tendency for site class condition. This study also proposed the empirical models in estimating V_{s30} and seismic vulnerability (K_g) indices for Bengkulu City. Those models are reliable in engineering practice application in Bengkulu City.

1. Introduction

Bengkulu City is known as one of tectonic active areas in Indonesia. This is due to the fact that several tectonic settings, such as Semangko Fault, Mentawai Fault, and Sumatra Subduction Zone exists in this area (Mase, 2017). Within last two decades, two strong earthquakes had occurred in Bengkulu City, Indonesia. The first one is Bengkulu-Enggano Earthquake occurred on June 4, 2000 with magnitude of 8.0 M_w and the second one is Bengkulu-Mentawai Earthquake occurred on September 12, 2007 with magnitude of 8.6 M_w (Figure 1). Mase (2017) mentioned that during those natural hazards, especially the Bengkulu-Mentawai Earthquake, massive damage on both structural buildings and soils were massively found. The soil damages such as liquefactions, ground failures, and ground cracks during the large earthquakes in Bengkulu City had been also reported by many researchers, such as Mase and Sari (2015), Mase and Somantri (2016), Mase (2017), and Mase (2018a). In general, the massive soil damage found in Bengkulu City had been occurred along coastal area of Bengkulu City. Those previous researchers had also reached the conclusion that the main factors triggering liquefaction along coastal area of Bengkulu City during both large earthquakes was not only the earthquake characteristic but also the geological and site conditions in Bengkulu City. Mase et al. (2018a) performed a seismic hazard analysis to Bengkulu City and recommended that the site effect could be the main reason in governing the damage

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Note : Discussion on this paper is open until June 2021

intensity during the earthquake. Learning from conclusions of those previous studies, the site investigation related to site condition should be the priority.

In general, there are two common methods normally performed to characterise the sites in Bengkulu City, i.e. the active method using multichannel analysis of surface waves (MASW) and another method called passive method by using microtremor. The geophysical measurements had been performed by several local researchers. Refrizon et al. (2013) performed the geophysical survey to investigate the local site condition in Ratu Agung District of Bengkulu City by using the microtremor measurement. Lestari et al. (2018) conducted the microtremor measurement to investigate the local site condition in Gading Cempaka and Ratu Agung Districts. Naibaho (2019) performed the microtremor measurement to Muara Bangkahulu District Sites. Those previous studies had generally reached the conclusion that the investigation areas in Bengkulu City is dominated by Site Classes D and C based on National Earthquake Hazard Reduction Provisions or NEHRP (1998). The investigation to measure shear wave velocity at several sites in Bengkulu City had been also performed by several researchers. Mase and Somantri (2016) employed the seismic downhole test to investigate liquefaction potential along coastal area of Bengkulu City based on Andrus et al. (2004) approach. Mase and Somantri (2016) in their study used the shear wave velocity data as the main parameter to justify liquefaction potential corresponding to the field evidence found during the Bengkulu-Mentawai Earthquake in 2007. Mase (2018a and Mase 2018b) used Spectral Analysis of Surface Waves (SASW) Method to measure the shear wave velocity along coastal area of Bengkulu City, which is indicated as the most impacted area during the Bengkulu-Mentawai Earthquake. The main purpose of this investigation is for the simulation of seismic ground response analysis. Suhartini (2019) performed the site investigation using the MASW and Microtremor to obtain the geophysical characteristic of Ratu Agung Site. In their current study, the parameters, such as maximum peak ground acceleration, the amplitude, and predominant frequency were observed. In general, the previous researchers had reached the conclusion that there is the importance of local site condition inspection in studying the seismic hazard analysis in Bengkulu City. However, the detail presentation related to the comparison of both methods and the use for the engineering practise for the model prediction associated with the geophysical characteristic has not been developed.

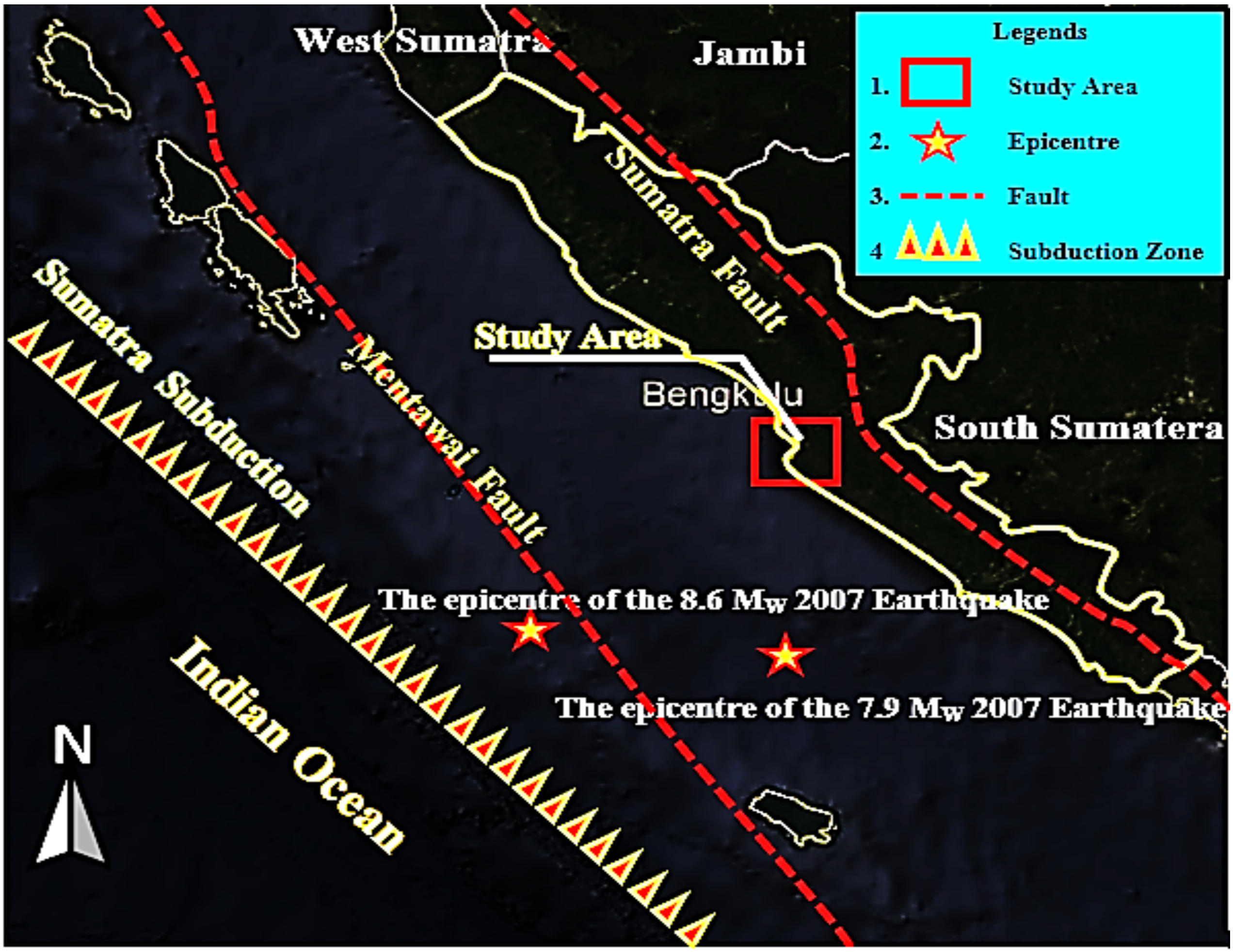


Figure 1. The location of study area (modified from Mase (2017))

This paper presents a comparative study of MASW and Microtremor Methods. The measurement of the shear wave velocity is performed. Th results of measurement are furthermore used to estimate the time-averaged shear wave velocity for the first 30 m depth (V_{s30}). The geophysical properties related to the Horizontal to Vertical Spectral Ration or H/V and predominant frequency are also performed. This study also proposed the empirical model to estimate the V_{s30} which is correlated to peak H/V (A_0) and f_0. For the engineering practice, the vulnerability index (K_g) model to measure the level of potential seismic damage in Bengkulu City is also proposed. The validation to the previous studies at the similar sites is also conducted to observe the performance of the proposed models. In general, the results of this study would deliver the benefit to the local engineers in studying local site condition for seismic hazard analysis necessary in Bengkulu City.

2. Study Area

This study is focused in Bengkulu City. Total of 35 sites (symbolised by yellow pins) are investigated in this study. At those sites, the geotechnical investigation and geophysical survey using ambient noise measurement and multichannel analysis of surface waves. The location of site investigation is presented in Figure 2.

In Figure 2, the sites are investigated by geotechnical method, such as boring log and cone penetration test (CPT) and geophysical surveys by microtremor to measure ambient noise and MASW. Based on site investigation results, the typical geological condition of Bengkulu City is summarised in Table 1. In Table 1, it can be seen that there are several soil layers types in Bengkulu City. The first one is organic clay (OH) and high plasticity clay (CH). These soil types are found at shallow depth, i.e. 0 to 1 m, with the unit weight (γ) of about 17 to 18 kN/m^3 and cone resistance (q_c) of about 2 to 10 kg/cm^2. Silty Clay (CM) is found on depth range of 1 to 3 m depth. This layer has γ of about 17 to 18 kN/m^3 and q_c of about 10-30 kg/cm^2. At the depth range of 3 to 18 m, the layers dominated by silty sand (SM), poorly graded sand (SP), and clayey sand (SC) exist. γ and q_c of the layers are about 18 to 21 kN/m^3 and 30 to 80 kg/cm^2, respectively. At depth of 18 to 40 m, the layers are dominated by well graded sands (SW) and clayey gravel (GC). γ and q_c range from 19 to 22 and 80-250 kg/cm^2, respectively. For Bengkulu City, the engineering bedrock depth is normally found on the layers deeper than 40 m depth. γ of the engineering bedrock is about 22 kN/m^3. The soil resistance of the engineering bedrock is more than 250 kg/cm^2.

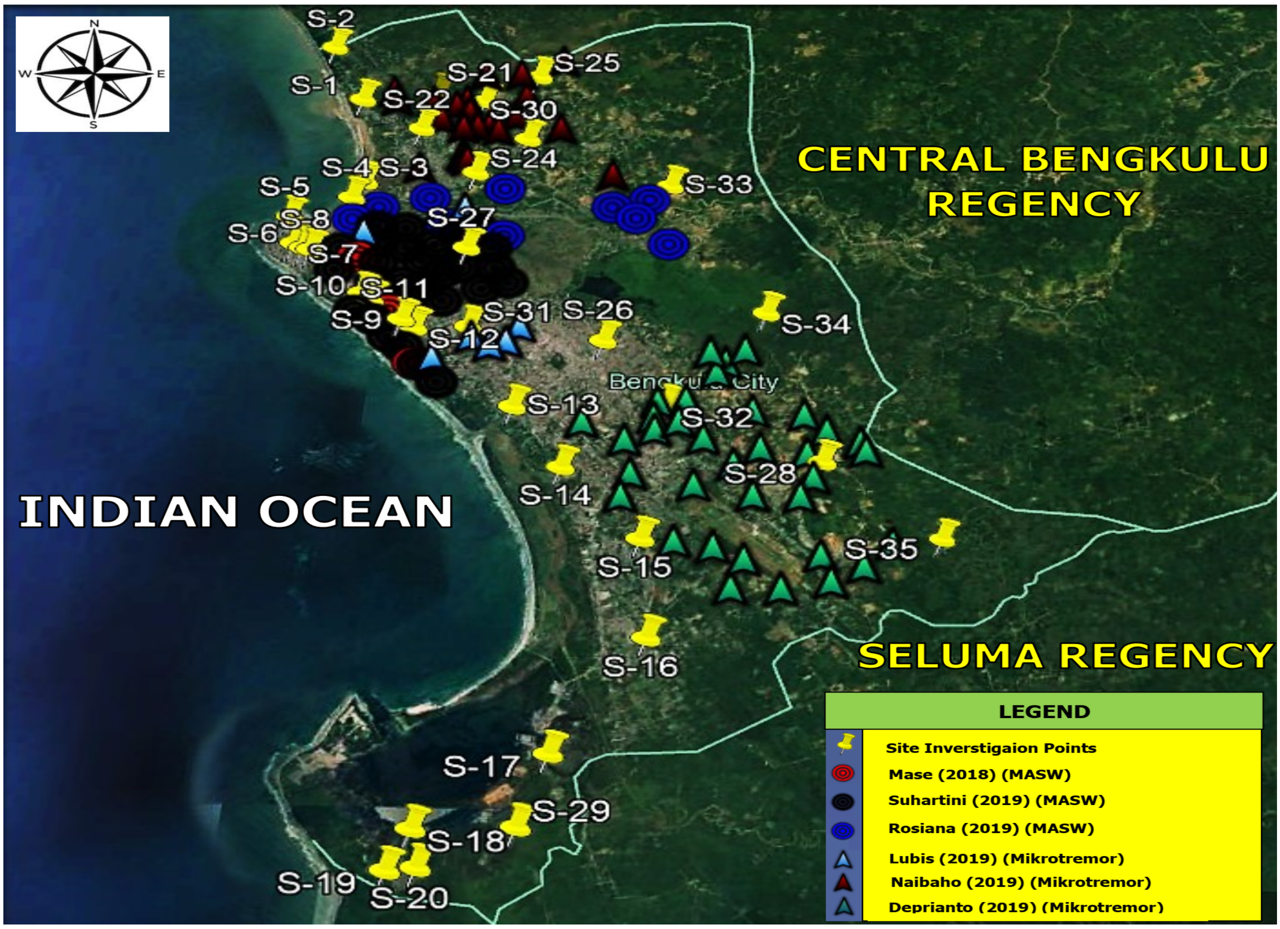


Figure 2. Site investigation layout

Table 1. Summary of typical geological condition of Bengkulu City

Depth (m)	Soil Type (USCS)	Unit Weight (γ) (kN/m^3)	Resistance (q_c) (kg/cm^2)
0-1	OH/CH	17-18	2-10
1-3	CM	17-18	10-30
3-18	SM, SP, SC	18-21	30-80
18-40	SW, SC, GC	19-22	80-250
>40	Rock	>22	>250

3. Theory and Methodology

3.1 Ambient noise measurement using microtremor

The application of microtremor to measure the ambient noise had been presented by several researchers, such as Mase et al. (2018b), El-Hady et al. (2012), Bard (2004), and Lachet et al. (1996). In microtremor measurement, the assumption of horizontal motion consisted of shear wave is implemented. The spectral of horizontal motion describes that the geophysical characteristic such as predominant period (T) and horizontal to vertical spectral ratio (H/V). Kanai and Tanaka (1954) proposed the empirical method to estimate H/V based on microtremor observation. This method was later widely popularised by Nakamura (1989) for engineering purpose to characterise the sites. The concept of this method is based on the spectral ratio of horizontal to vertical which is obtained from the ambient noise measurement. In the application, the H/V ratio corresponding to frequency (f) is depicted. From the interpretation, the peak H/V or amplitude and predominant frequency (f_0) can be defined. Atakan (2009) in Mase et al. (2018b) stated that the H/V ratio measured from the ambient noise measurement was relatively consistent with H/V ratio recorded on the surface of sediments to the bedrock at the bottom of sediment layer. The H/V method is also employed to obtain the site information, such as shear wave velocity, which is used for several purposes, such as seismic ground analysis.

The H/V ratio is calculated based on the Fourier Amplitude Resultant on horizontal to vertical components, which is expressed in the following equation,

$$H/V = \sqrt{\frac{H_{(EW)}^2 + H_{(NS)}^2}{2V^2}} \quad (1)$$

where, *H/V* is the horizontal to vertical spectral ratio. $H_{(EW)}$ and $H_{(NS)}$ are the Fourier amplitude spectra of the horizontal in the EW and NS directions, respectively, and *V* is the Fourier amplitude spectra of vertical direction.

For engineering practice, the microtremor measurement results can be used to estimate the seismic vulnerability index or K_g (Nakamura et al., 1999). The equation to estimate the seismic vulnerability index (K_g) can be expressed in the following,

$$K_g = \frac{A_0^2}{f_0} \quad (2)$$

where, A_0 is peak value of H/V curve and f_0 is the predominant frequency of each. In the implementation, K_g is used as the preliminary justification of seismic hazard vulnerability area.

In general, based on the experimental research, H/V ratio is relatively more stable than the raw noise spectra (Koçkar and Akgün, 2012). For ease, the peak amplitude of H/V is also able to be well correlated with predominant frequency (f_0), especially soft soil sediment. However, the noise effect, environmental setting, other surficial disturbances could affect the accuracy of measurement. Therefore, the H/V definition is still becoming the issue in the H/V method. Lachet and Bard (1994) mentioned that the minimalization of noise could be the manner to provide the best description of sedimentary layer. H/V method is generally successfully to estimate predominant frequency, but it is not totally able to capture the clear peak of H/V (Bonnefoy-Claudet et al. 2006). Raptakis et al. (2005) mentioned that even though, the H/V method is intensively debated, the use of predominant frequency from ambient noise measurement is still widely performed.

A broad band seismometer called PASI Gemini (triaxial geophone) are used to measure the ambient noise in this study. This equipment consisted of three accelerometers components, i.e. east-west, north-south, and up-down (vertical). This equipment is developed to observe the strong and weak motions. The sampling rate of this equipment ranges from 20 Hz to 8000 Hz. Each measurement is performed for 30 mins. Before measurement, the warming up for the digitisers is implemented for about 5 mins. This treatment is expected to avoid the problem of low frequency range and to obtain the reliable measured data. Once the measurement is completed, the noise from the recorded data is removed. In this study, procedure of microtremor measurement to the selection of ambient noise for the processed data is based on the criteria provided by SESAME (2004). The reliable noise is then analysed to generate the H/V curve. H/V curve is further analysed to generate the shear wave velocity (V_s) profile using the model proposed by García-Jerez et al. (2016). This model is developed for the inversion analysis, which is computed based on Monte Carlo Sampling Simulated Annealing García-Jerez et al. (2016).

The model of García-Jerez et al. (2016) required 5 important parameters for each layer. They are the soil thickness, pressure wave velocity (V_p), shear wave velocity (V_s), soil's density (ρ), and Poisson's ratio (ν). At the bottom of layer, the elastic half space assumption is implemented. For Monte Carlo simulation, each parameter is ranged from the minimum to maximum value, which is defined from the a priori knowledge of soil properties of materials (Wathelet, 2008). In this study, the values of soil parameters on each layer is derived from the information of typical soil layer in Bengkulu City, which is summarised in Table 1. The shear wave velocity is derived from the correlation equation of V_s and q_c and/or N-SPT based on study of Imai and Tonouchi (1982). V_s is also able to predict from the elastic theory which correlates to the

Poisson ratio and elastic modulus (Salencon, 2001). To predict V_p, the ratio of V_p/V_s is also firstly assumed in the model (Tatham, 1982). Several researchers, such as Wathelet (2008), García-Jerez et al. (2016), Mase et al. (2018b) mentioned that V_p, V_s, and Poisson's ratio are categorised as the independent parameters. In the analysis, Monte Carlo simulation is initiated with starting guess model that has parameters listed in Table 2. The geotechnical parameters such as thickness, V_p, V_s, ρ is calculated repeatedly until the H/V curve from the field measurement was consistent or matched with the calculated H/V curve.

3.2 Multichannel analysis of surface wave

In 1999, the extended method of spectral analysis of surface waves (SASW) called multichannel spectral analysis of surface waves (MASW) was proposed by Park et al. (1999). Generally, the surface-wave analysis is expected to be accurate in estimating the phase velocities for the horizontally traveling fundamental-mode Rayleigh wave. Based on that concept, Nazarian et al. (1983) proposed the SASW method, which is now widely used in solving the problem of geotechnical engineering, particularly the estimation of V_s. SASW uses the two receivers which is arranged to sample the needed frequency range. Furthermore, data are analysed to obtain the dispersion curves. The noise during SASW measurement is usually able to be eliminated by an empirical criterion for the investigated points (Stokoe et al., 1994). However, the challenging of this method is the optimisation of the used data, since there is a possibility of changes due to the noise, at near surface materials (Park et al., 1999). The expensive cost and much time to repeat the record for ensuring the record could be another issue in the use of SASW method.

The implementation of MASW is expected to minimise the weakness of SASW method. Park et al. (1999) mentioned that MASW permits the effective identification and isolation of noise according to distinctive trace to trace coherency in arrival time and amplitude. MASW method is implemented based on the dispersion of Rayleigh wave through the soil layers. The different travel length means the different thickness of subsoils. The general procedure of MASW include the acquisition, processing, and inversion (Eikmeier et al., 2016). The acquisition step is performed by producing the energy to generate seismic wave. For this step, a sledge hammer and/or drop weight hammer are used. The propagated wave in form of seismic wave is then recorded by a set of linear geophones. In this study, total of 24 geophones of 4.5 Hz is used during the measurement. Once the acquisition step is completed, the next following step is the processing. In this step, the dispersion curve is extracted from the record. The dispersion curve is presented in the form of phase velocities against frequency. The last step is inversion analysis. In this study, the analysis of inversion refers to the geological condition obtained from site investigation as well as the typical of subsurface in Bengkulu City. The inversion analysis is performed by the iteration process. The iteration is operated based on the framework of stiffness matrix method for layered system (Kausel and Roesset, 1981). Similar with the inversion method of H/V curve, the inversion of MASW dispersion curve is continually performed until the theoretical curve is matched with the measured curve.

3.3 Local site condition

National Earthquake Hazard Reduction Provisions or NEHRP (1998) released the criteria to determine the local site condition. The criteria are arranged based on the time-averaged shear wave velocity up to first 30 m depth (V_{s30}), which is expressed in the following equation,

$$V_{s30} = \frac{30(m)}{\sum_{i=1}^{n} \frac{d_i}{V_{si}}} \tag{2}$$

with d_i is the thickness of each soil layer, V_{si} is the shear wave velocity of each soil layer and n is total number of soil layers considered up to first 30 m depth.

Table 3 summarises the range of V_{s30} corresponding to site class proposed by NEHRP (1998). In general, the analysis of V_{s30} is performed for the site which has the investigated depth of 30 m. However, for several cases, due to the uniqueness of the site condition, the shear wave velocity measurements are only able to perform less than 30 m depth. Regarding this condition, the statistical extrapolation method can be used to predict V_{s30} (Boore, 2004). The equation to predict V_{s30} using the statistical extrapolation method is expressed in the following,

$$V_{s30} = 10^{\left(a + b\log\left(V_{s(d)}\right)\right)} \tag{3}$$

where a and b are the statistical extrapolation values corresponding to the depth of bottom velocity.

The implementation of V_{s30} is not only related to the classification of site, but also related to the prediction of ground motion parameters, such as peak ground acceleration and spectral acceleration (Mase et al., 2018b). Several researchers such as Mase et al. (2018c), Mase (2017), Abrahamson et al. (2014), Boore et al. (2014), Campbell and Bozorgnia (2014), Chiou and Youngs (2014), and Idriss (2014) had stated that the uncertainty of site condition representing by V_{s30} is very important in determining the ground motion parameters. Therefore, obtaining the value of shear wave velocity and site class condition should be carefully considered in earthquake engineering.

3.4 Research framework

This study is initiated by performed site investigation in the study area, i.e. Bengkulu City. Total of 35 sites which spread in the Bengkulu City, are investigated in this study. The cone penetration test and boring log are performed to determine the information of subsoils characteristic in the study area. At those site investigation points; the geophysical measurements are also performed. In this study, the microtremor and MASW measurements are performed to obtain the geophysical characteristics, which are addressed for the necessary to understand the local site condition. For microtremor results, the analysis of K_g is also performed to determine the characteristic of seismic hazard tendency in Bengkulu City. The data collected from the measurement are then processed to derive the local site description, i.e. H/V curve for microtremor and dispersion curve for MASW. The inversion analysis is furthermore performed to generate the shear wave velocity profile on each investigated site. The inversion is completed once the observed data are matched with the calculated data. The shear wave velocity profiles generated from the inversion analysis for each measurement is compared each other. The site class analysis is also performed to obtain the information of local site condition. The site class estimation from both measurements are also compared each other. From the results of analysis, the empirical correlation (for both measurements) based on the geophysical characteristic such as A_0 and f_0 are generated to estimate V_{s30}. Besides, for engineering practice in estimating the seismic vulnerability, the empirical correlation (for both measurements) based on A_0, V_{s30} and f_0 are also proposed. To examine the reliability of the proposed models, the validation to the field measurements performed by previous studies is performed. Those proposed correlations would give the benefit in predicting V_{s30} without the inversion process for the study area of Bengkulu City. In general, the results of this study could give the better description of the geophysical measurement in Bengkulu City. In addition, the results of this study could give a recommend to the local engineering to reconsider the local site condition in earthquake engineering aspect. The proposed empirical correlations could be implemented for the simple purpose in engineering practise.

4. Results and Discussion

4.1 Shear wave velocity of microtremor

The location of site investigation was presented in Figure 2. The measurement of microtremor was performed for 25 minutes. The measured data was ambient noise record. The measurement is performed based on guidelines suggested by SESAME (2004). This data was then processed to generated the H/V curve. H/V curve represents the impedance contrast between the sediment and bedrock. For the example, the site S-2 is presented in Figure 3a. In S-2, the H/V values is plotted corresponding to frequency. The peak H/V or amplification for this site is about 2.735 with predominant frequency of about 2.315 Hz. According to SESAME (2004) guidelines, the sediment of S-2 is categorised as medium impedance soils. This method is also implemented by Gosar et al. (2010) to observe the soil impedance of Slovenia Furthermore, the H/V curve from the microtremor measurement is analysis using the inversion method proposed by García-Jerez et al. (2016). In this study, the initial model presented in Table 2 is used. The result of inversion analysis is presented in Figure 3b. In general, the inversion curve is relatively consistent with the measured H/V. The inversion analysis result is then generated to the shear wave velocity (V_s) profile, as presented in Figure 4. In Figure 4, it can be seen that the shear wave velocity obtained from the inversion analysis is generally consistent with the MASW measurement (detailed in Section 4.2). Based on the inversion analysis shear wave velocity increases with depth and consists 4 soil layers. The soil type in S-2 is dominated by silty clay (CM) and silty sand (SM). From the shear wave velocity profile, V_{s30} is furthermore calculated by using Eq (2). The results showed that V_{s30} of S-2 is about 365 m/s. It indicates that the S-2 site is categorised as Site Class C. Overall, the investigated sites have V_{s30} ranging from 261 m/s to 572 m/s. It indicates that site classes in Bengkulu City can be categorised as Site Class C to Site Class D. The detail explanation for the comparison of V_{s30} for each site class can be found in Section 4.3.

4.2 Shear wave velocity of MASW

Similar with microtremor measurement, MASW measurements were also performed to the investigated sites. The procedure of MASW measurement followed the recommendation suggested by Park et al. (1999). In this study, 24 geophones with 1 m space and 4 me offset were used for MASW measurements. The seismic source was a sledge hammer. The signal of Rayleigh wave was then recorded by seismograph, which was later filtered out to minimise the noise. The wave dispersion was then interpreted and transformed into shear wave velocity. Similar with microtremor measurement, the shear wave velocity profile was also interpreted for first 30 m depth. The example of dispersion curve (S-2) in this study is presented in Figure 5. In general, the tendency of shear wave velocity from MASW measurement is also similar with shear wave velocity of microtremor. Shear wave velocity profile generally increases with depth. Based on the estimation of Vs_{30}, Site S-2 has Vs_{30} of about 388 m/s. Similar with microtremor measurement, S-2 has been also categorised as Site Class C. Generally, the site class of Bengkulu City based on MASW measurement ranged from 261 to 572 m/s.

4.3 Comparison of V_{s30} from Inversion and MASW

The comparison of V_{s30} inversion and V_{s30} MASW is presented in Figure 5. As presented in Figure 5, V_{s30} obtained from MASW measurement tends to be larger than V_{s30} obtained from Inversion of ambient noise from microtremor measurement. This may be caused by the extrapolation method of V_s on the last layer, which has not reached 30 m deep, especially for MASW Measurement. The effect of extrapolation method to V_s on the last layer had been also reported by Mase et al. (2018b) who studied the local site condition of liquefied locations during Mae

Lao Earthquake in Northern Thailand. However, both results of V_{s30} from inversion and MASW measurement show the same tendency of the Site Classes C and D. The results also agree with the geophysical tests performed by Mase et al. (2018a), Naibaho (2019), Rosiana (2019), Lubis (2019), and Deprianto (2019) as well as the seismic analysis performed by Mase and Somantri (2016). All studies reported that Bengkulu City could be categorised as Classes C and D.

4.4 Vulnerability index (K_g) of Bengkulu City

The interpretation of vulnerability index (K_g) corresponding to f_0 and A_0 is presented in Figure 6. Those parameters are obtained from microtremor measurements. Both A_0 and f_0 are then used to calculate K_g. From the interpretation in Figure 6, A_0 of Bengkulu Sites ranges from 1 to 7, whereas f_0 of Bengkulu Sites ranges from 0.89 to 21.2 Hz. According to Gosar (2010) study, the sites with low predominant frequency indicates that there is a thick sediment thickness underlain by bedrock and vice versa. In Bengkulu City, the geological condition is relatively complex. Mase et al. (2018) reported that Bengkulu City has various geological condition dominated by Qa (alluvium), Bintunan Formation (QTb), Reef limestone (Ql), Swamp Deposit (Qs), Alluvium Terraces (Qat), and Andesite (Tpan). Several studies of geological formation in Bengkulu City had been performed. Lubis (2018) studied that Qat and QTb formations concentrated along coastal area of Bengkulu City tends to have f_0 ranging from 1.09 to 11.24 Hz and A_0 ranging from 1.09 to 4.14. Rosiana (2019) mentioned that Qs, QTb and Qa formations in Bengkulu City had f_0 ranging from 0.67 to 8.96 Hz and A_0 ranging from 2.53 to 8.56. Naibaho (2019) stated that QTb, Qa, Qs, and Qat formations in Bengkulu City had A_0 of about 0.73 to 4.72 and f_0 of about 0.73 to 16.87 Hz. Deprianto (2019) also explained that Tpan and QTb formations had A_0 of about 1.82 to 5.72 and f_0 of about 0.80 to 16.27 Hz. In general, those previous studies are consistent with this study. Figure 6 also explained that generally, the smaller amplification or peak H/V (A_0) and the larger predominant frequency (f_0) means the smaller K_g and vice versa. Based on the interpretation, K_g of Bengkulu Sites ranges from 0.1 to 8. Mase (2019) mentioned that the K_g in Bengkulu City, especially along coastal area of Bengkulu City is normally ranging from 1 to 4. Mase (2018b) also reported that liquefied sites located in Qa formation has K_g of about 3 to 8. Generally, the result of this study relatively consistent with previous studies.

Figure 7 presents the interpretation of K_g corresponding to V_{s30}. From Figure 7, it can be seen that both V_{s30} resulted from Inversion and MASW show the similar tendency corresponding to K_g. In general, the larger V_{s30} means the smaller K_g and vice versa. A smaller V_{s30} indicates that the site is relatively vulnerable to undergo seismic damage (Mase et al., 2018b). Therefore, a more vulnerable site means a larger vulnerability index.

4.5 Proposed formulations to estimate V_{s30} based on A_0, f_0, and K_g

To encourage the use of formulation for the engineering practice in Bengkulu City, several formulations generated to estimate V_{s30} and K_g are proposed. In this study, the proposed models to estimate V_{s30} are analysed using the multiple linear regression. Several parameters (A_0, f_0, and K_g) are used as the components to generate empirical models.

The proposed models to estimate V_{s30} for Bengkulu City is presented in these following equations,

$$V_{s30}\ \text{MASW} = 59.485A_0 + 17.291f_0 + 30.478K_g \quad (4)$$

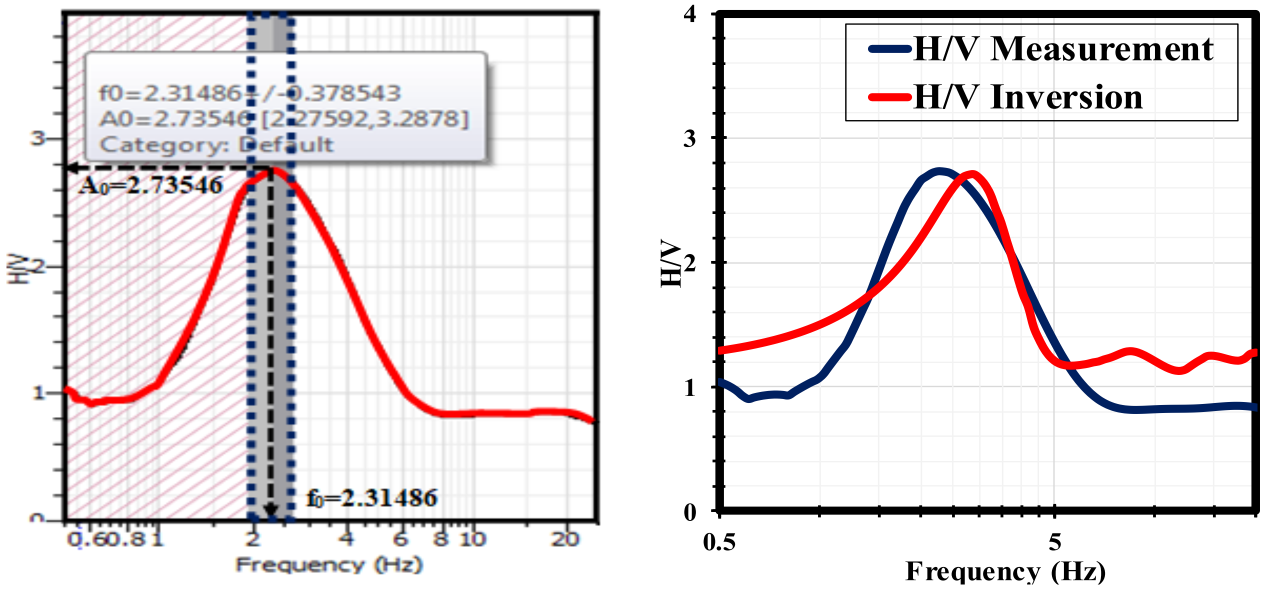
$$V_{s30}\ \text{Inversion} = 50.694A_0 + 14.394f_0 + 28.142K_g \quad (5)$$

For MASW, R^2 is 0.851, Multiple R is 0.922, and Adjusted R^2 is 0.789, respectively. For Inversion R^2 is 0.835, Multiple R is 0.914, and Adjusted R^2 is 0.806, respectively.

The performance of the proposed models corresponding to the influenced factors is presented in Figure 8 to 10. Figure 8 presents the interpretation of V_{s30} and A_0. Generally, predictions show the tendency that the larger A_0 means the larger V_{s30}. For V_{s30} of MASW, the models relatively well captured for the site with A_0 within 2 to 5. For A_0 larger than 6 and less than 2, the models are not relatively able to capture the V_{s30}. For V_{s30} of inversion, the model relatively well captured V_{s30} for the site having A_0 of about 2 to 4.5. Similar with V_{s30} of MASW model, the model of V_{s30} inversion is also relatively not well capturing for A_0 larger than 4.5. and less than 2. Figure 9 presents the interpretation of V_{s30} and f_0. Figure 9 explains that the models are relatively well capturing V_{s30} from both MASW and microtremor measurements for f_0 of about 1 to 8 Hz. Generally, the predictions resulted from both models are relatively lower conservative. Figure 10 presents the interpretation of V_{s30} corresponding to K_g. As presented in the previous section, V_{s30} has the correlation to K_g. From Figure 10, it can be seen that the models are generally well capturing V_{s30} for K_g values of about 1 to 4. The prediction is relatively lower conservative for K_g larger than 4.

Table 2. Range values of initial parameters for H/V inversion

Layer	Soil Type USCS	Thickness (m)	V_s (m/s)	V_p (m/s)	Density (ρ) (kg/cm^3)	Poisson Ratio (ν)
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
5	Rock	~	500-760	750-1140	2000-2200	0.100-0.300



(a) (b)

Figure 3. H/V curve of M-2 (a) measurement result (b) comparison between inversion and measurement

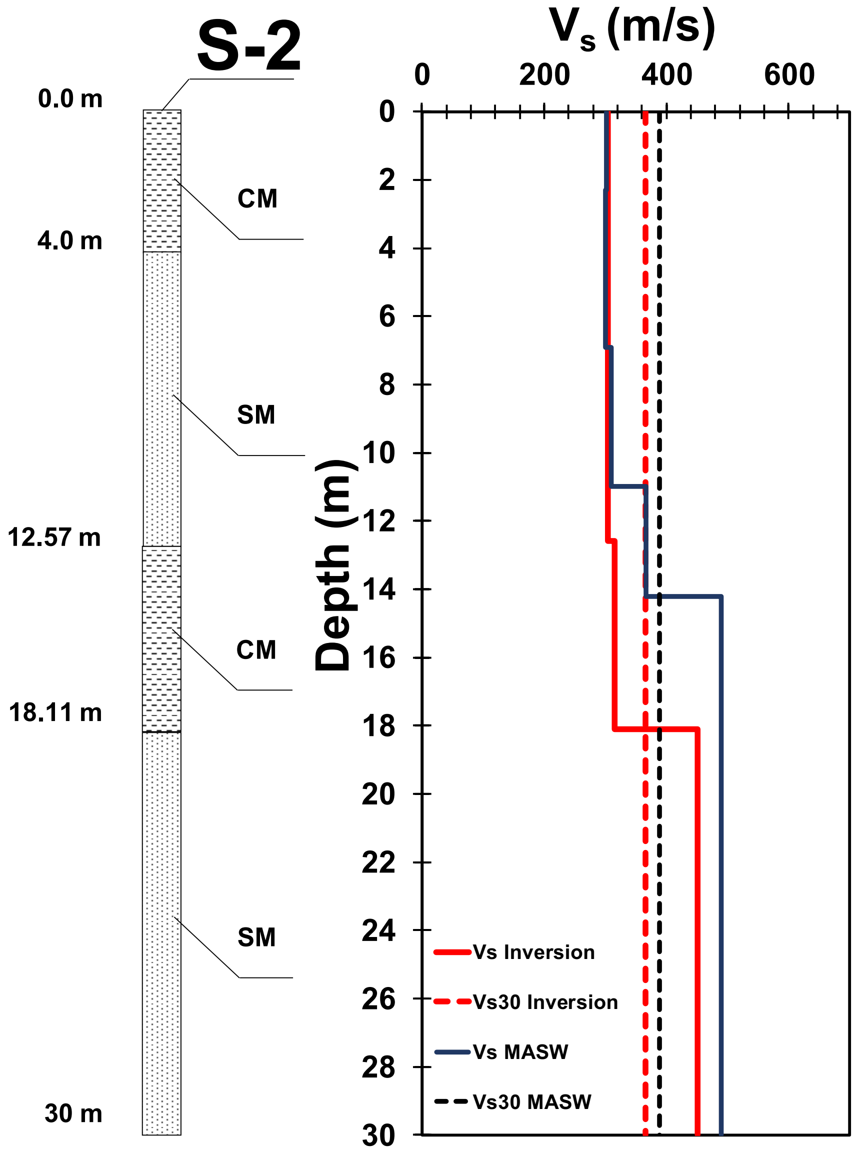


Figure 4. Shear wave velocity and Shear wave velocity for first 30 m depth from the inversion analysis and MASW

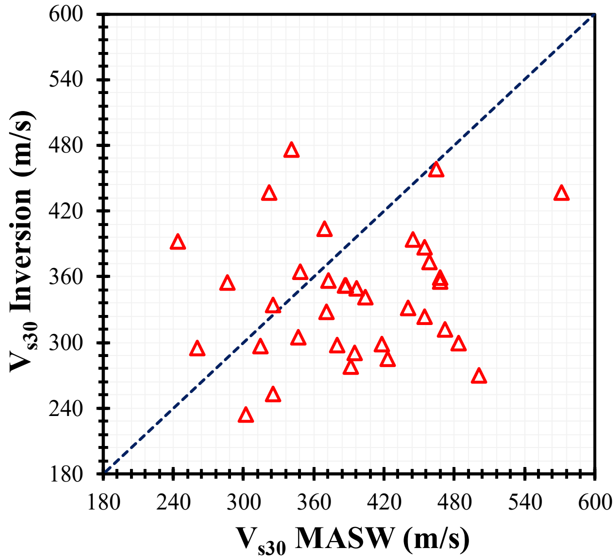


Figure 5. Comparison of Shear wave velocity for first 30 m depth from the inversion analysis and MASW measurement

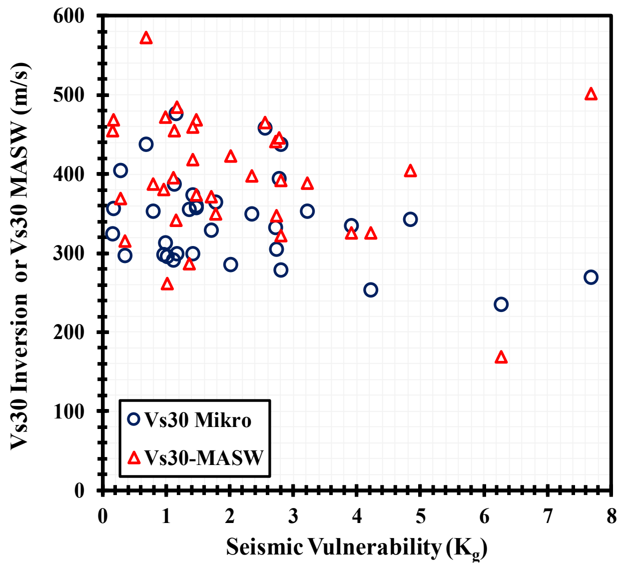


Figure 6. Comparison of K_g corresponding to A_0 and f_0 for Bengkulu Site

Generally, the models had given the promising practical method to estimate to V_{s30} for Bengkulu City. However, there are several inconsistent predictions resulted from the model. The inconsistent prediction could be caused by the effect of uncertainty of the site. Seyhan et al. (2014) mentioned that the larger prediction of V_{s30} may be caused by the uncertainty on the investigated depth. The uncertainty on the investigated sites can be caused the by the effect of near surface. Derras et al. (2017) mentioned that the near surface deposits strongly influenced the uncertainty. Therefore, the further investigation related to geological condition, such as boring log can help to understand the effect of soil deposits in shear wave velocity measurement. However, the average relative uncertainty for the proposed models are about of 20.17% to 26.6%, which based on Mulargia and Castellaro (2009) are still acceptable as the uncertainty on V_{s30}. Mulargia and Castellaro (2009) mentioned that total investigated points more than 10 should be used to achieve the worthwhile estimate of experimental scatter. Since this study used 35 investigated points, the proposed model is still able to be used for engineering practice. The performance of the models in predicting V_{s30} in Bengkulu Sites is presented in the next section.

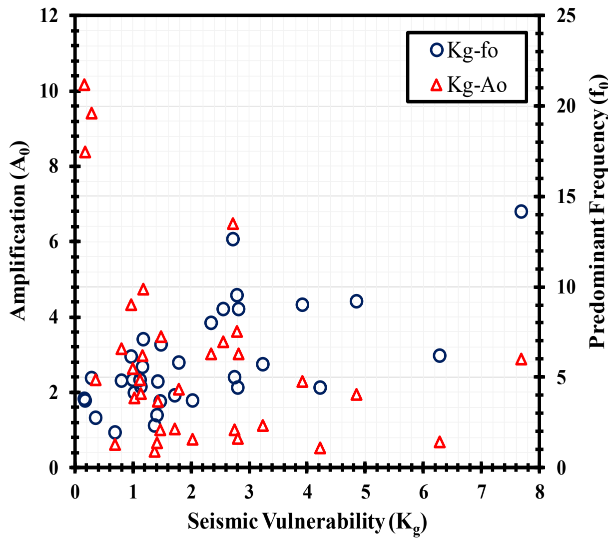


Figure 7. Comparison of K_g corresponding to V_{s30}

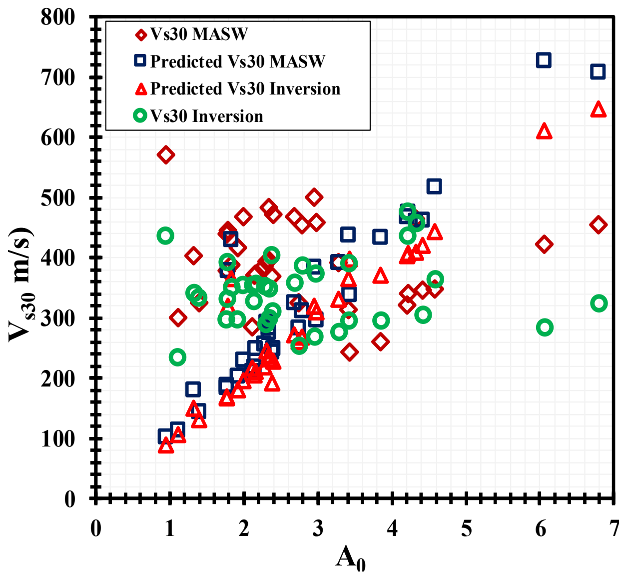


Figure 8. Interpretations of V_{s30} corresponding to A_0,

4.6 Performance of the models to predict V_{s30} in Bengkulu Sites

To observe the reliability of the models in predicting the V_{s30} in Bengkulu Sites, the performance of the models is observed in this study. Several previous studies (Mase, (2018), Rosiana (2019), and Suhartini (2019) for MASW and Lubis (2019), Deprianto (2019), and Naibaho (2019) for microtremor measurements performed to obtain V_{s30} on specific sites in Bengkulu City are examined by the proposed models. The location of site investigation performed by previous studies is presented in Figure 2. Figures 11 and 12 presents the interpretation V_{s30} MASW (Figure 11) and V_{s30} inversion (Figure 12) models examined to the measured V_{s30} obtained from MASW and microtremor measurements. In these figures, it can be seen that the calculated V_{s30} values are relatively larger than the measured value. The tendency of suitability values of this comparison is also presented by coefficient of linear regression (R^2). R^2 values for both models' predictions are 0.976 and 0.992, respectively. It indicates that the V_{s30} MASW model is relatively reliable in predicting V_{s30} in Bengkulu City for MASW measurement. The performance of the models in predicting V_{s30} had shown the alternative for the local engineers to solve the problem of site class in Bengkulu City. In the future, the implementation of V_{s30} can be used as the alternative to characterise local site condition in Bengkulu City.

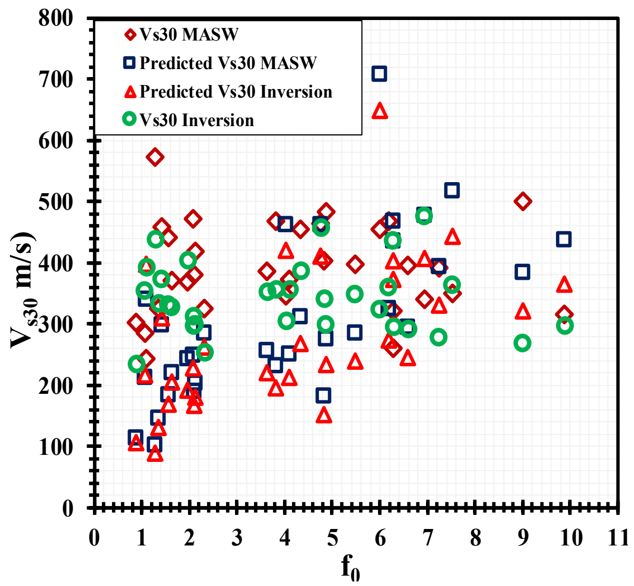


Figure 9. Interpretations of V_{s30} corresponding to f_0

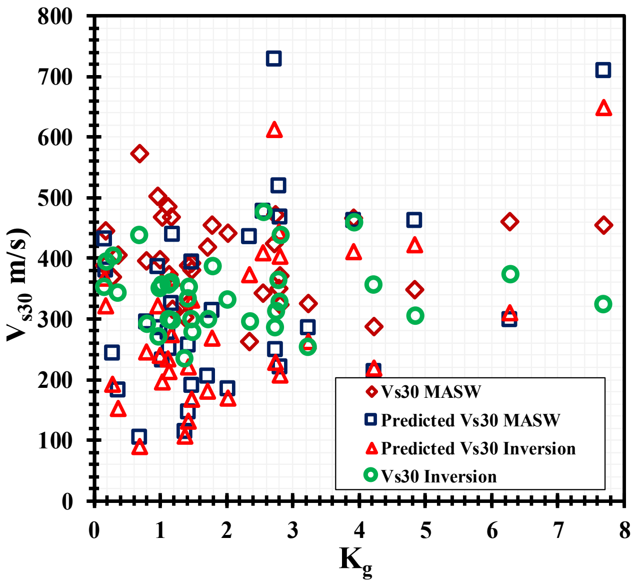


Figure 10. Interpretations of V_{s30} corresponding to K_g

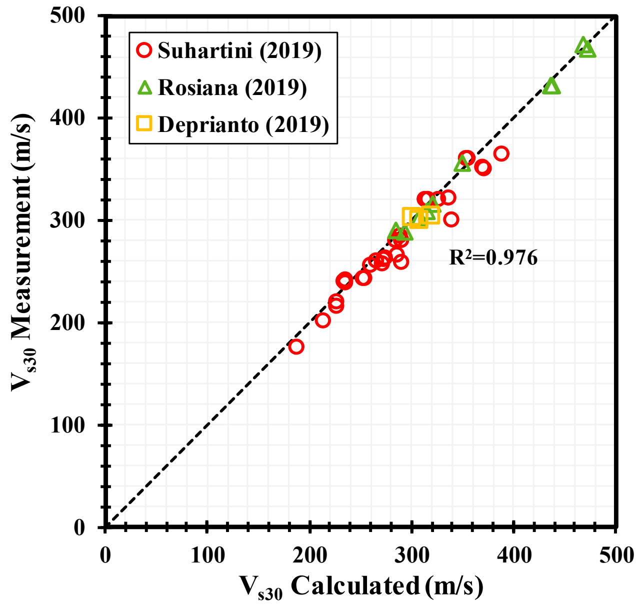


Figure 11. Validation of V_{s30} MASW model

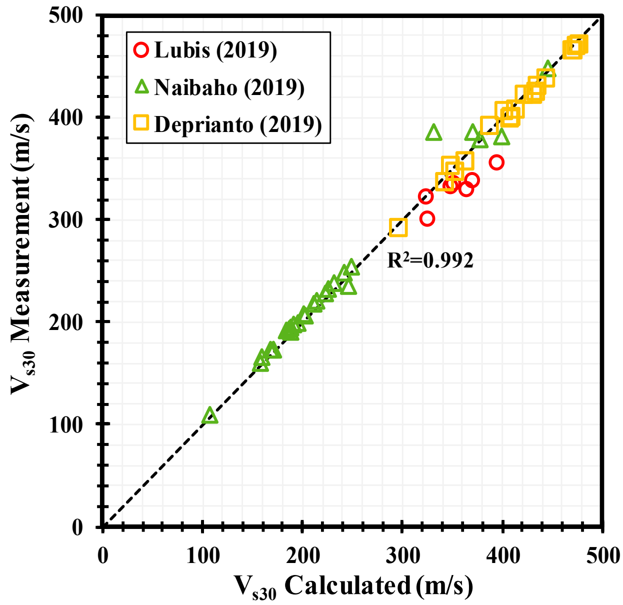


Figure 12. Validation of V_{s30} Inversion model

5. Concluding

This paper presents a comparative study of shear wave velocity measurement using active and passive methods. 35 sites are investigated by using MASW measurement and microtremor measurement. Furthermore, the shear wave velocity profile up to 30 m depth. V_{s30} obtained from both measurements is then compared each other. The models considered the local site parameters such as A_0, f_0, and K_g are then proposed.

In general, the site class of Bengkulu City is dominated by Site Class C dan D. Site class D is generally located along coastal area of Bengkulu City dominated by alluvium and alluvium terraces formations. These formations consisted of sandy soils, silty soils, and clayey soils. The sandy soils under saturated conditions are relatively vulnerable to undergo liquefaction during the earthquakes. It was confirmed by several liquefied soils found along coastal area of Bengkulu City, as reported by Mase (2017). The damage seems to be more serious for the sites having site class D. This is due to the fact that Site Class D has a lower shear wave velocity compared to Site Class C. Hausler and Anderson (2007) also reported that along coastal area of Bengkulu City, the structural buildings standing on location of Site Class D were generally collapsed during the Bengkulu Mentawai Earthquake. In terms of vulnerability aspect, the investigated sites have K_g of about 1 to 8. A larger K_g indicates a more vulnerable for the site undergo seismic damage during the earthquake. The prediction of K_g for Bengkulu Site is generally consistent with Mase et al. (2018b) and Mase (2019).

V_{s30} obtained from MASW measurement is relatively high conservative than V_{s30} of Inversion. This is due to the fact that for the analysis, the extrapolation method is implemented for the sites which has no shear wave velocity profile up to 30 m depth. The extrapolation method effect found in this study is generally consistent as reported by Mase et al. (2018b). However, both measurements generally showed the similar Site Classes, i.e. Site Class C and Site Class D. The consistent prediction of site class obtained from both measurements leads to the further analysis, i.e. the empirical models to predict V_{s30}. In general, the proposed models built from the local site parameters such as A_0, f_0, and K_g parameters are able to be adopted in engineering practice purpose. To test the reliability of the model, the validation should be hence performed. The performance of the models in predicting V_{s30} is generally good. The convincing R^2 values for both models (MASW and Inversion) explained that the models are reliable. The proposed models are also able to be a simple consideration to determine the local site characteristic in Bengkulu City. The models are also pretty promising for seismic hazard assessment in Bengkulu City.

Acknowledgement

This study is supported by the 2019 International Collaboration Research Funding No. 2183/UN30.15/LT/2019 and the 2018 Competitive Research Fund No. 2357/UN30.15/LT/2018 from the University of Bengkulu, Indonesia. The authors also would like to thank Geophysics Laboratory, Department of Mathematics and Natural Sciences, University of Bengkulu for geophysical measurements and Soil Mechanics Laboratory, Department of Civil Engineering, University of Bengkulu, for site investigation data.

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Symbols and abbreviations

V_s	Shear Wave Velocity
V_{s30}	The time-averaged shear wave velocity for first 30 m
K_g	Seismic vulnerability index
H/V	Horizontal to vertical spectral ratio
A_0	Amplification
f_0	*Predomimant frequency*
CPT	Cone penetration Test
MASW	Multichannels Analysis of Surface Waves
OH	Organic clay
CH	Clay with high plasticity
γ	*Unit weight*
q_c	Cone penetration
CM	Silty clay
SP	*Poorly graded sand*
SC	*Clayey sand*
SW	*Well graded sand*
GC	*Clayey gravel*
f	*Frequency*
EW	*East-West*
NS	*North-South*
$H_{(NS)}$	The Fourier amplitude spectra of the horizontal on EW direction
$H_{(EW)}$	The Fourier amplitude spectra of the horizontal on NS direction
V	Fourier amplitude spectra of vertical direction.
V_p	Pressure wave velocity
V_s	Shear wave velocity
ρ	Mass density
ν	*Poisson ratio*
N-SPT	*The value of standard penetration test*
Qa	*Alluvium formation*
QTb	*Bintunan Formation*
Ql	*Reef limestone*
Qs	*Swamp Deposit*
Qat	*Alluvium Terraces*
Tpan	*Andesite*
R^2	Coefficient of determination