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ORIGINAL PAPER

Local Site Investigation and Ground Response Analysis on Downstream Area of Muara Bangkahulu River, Bengkulu City, Indonesia

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Abstract One of the developing areas in Bengkuku City, Indonesia is the downstream of Muara Bangkahulu River. Therefore, this study aims to present an investigation of the local site and analysis of ground response in this area. Geophysical measurements were adopted in this research using multichannel analysis of surface wave and microtremor. Furthermore, field measurements were processed to interpret the characteristics of the ground surface, such as shear wave velocity (V_s) profiles, time-averaged shear wave velocity for the first 30 m depth (V_{s30}), and site classifications. The results show that the study area is categorised into Site Classes C and D. Also, the loose sedimentary soils exist at shallow depth and tend to be more vulnerable to undergo seismic phenomenon, which includes liquefaction and ground amplification. Generally, the results are expected to provide a better understanding of geophysical characteristics and earthquakes, which will help the local government to compose a spatial plan on the basis of seismic hazard mitigation.

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Keywords Geophysical measurement · Shear wave velocity · Site classification · Environmental setting · Seismic hazard mitigation

Introduction

Bengkulu City, the capital of Bengkulu Province, which frequently undergoes seismic hazard, is one of the developing areas in Indonesia. Mase [1, 2] mentioned that the City is very vulnerable to undergo earthquake impact and liquefaction. Under these complex circumstances, Farid and Mase [3] suggested that the local government needs to revise spatial plan every 5 years and consider the mitigation of seismic hazards for city development. This needs to be addressed to reduce the impact of natural disasters, which may become worse in the future [4].

The downstream of Muara Bangkahulu River, known as Sungai Serut District, has grown significantly to be one of the prospective areas in Bengkulu City (Fig. 1). Puteri et al. [5] predicted a high distribution pattern for the population of Bengkulu City in 2032, especially in Sungai Serut District. Furthermore, Puteri et al. [5] mentioned that the local government needs to take action in response to this issue by strengthening the regulation of land use. Moreover, Farid and Mase [3] recommended the development of spatial plan based on seismic hazard mitigation. Before developing a policy to cover the issue, a study of the environmental condition on several specific areas needs to be first prioritised. For instance, the geophysical characteristic of subsoil's condition and site classification need to be considered. This will help the local government to completely understand how to define the vulnerability level of the hazard.

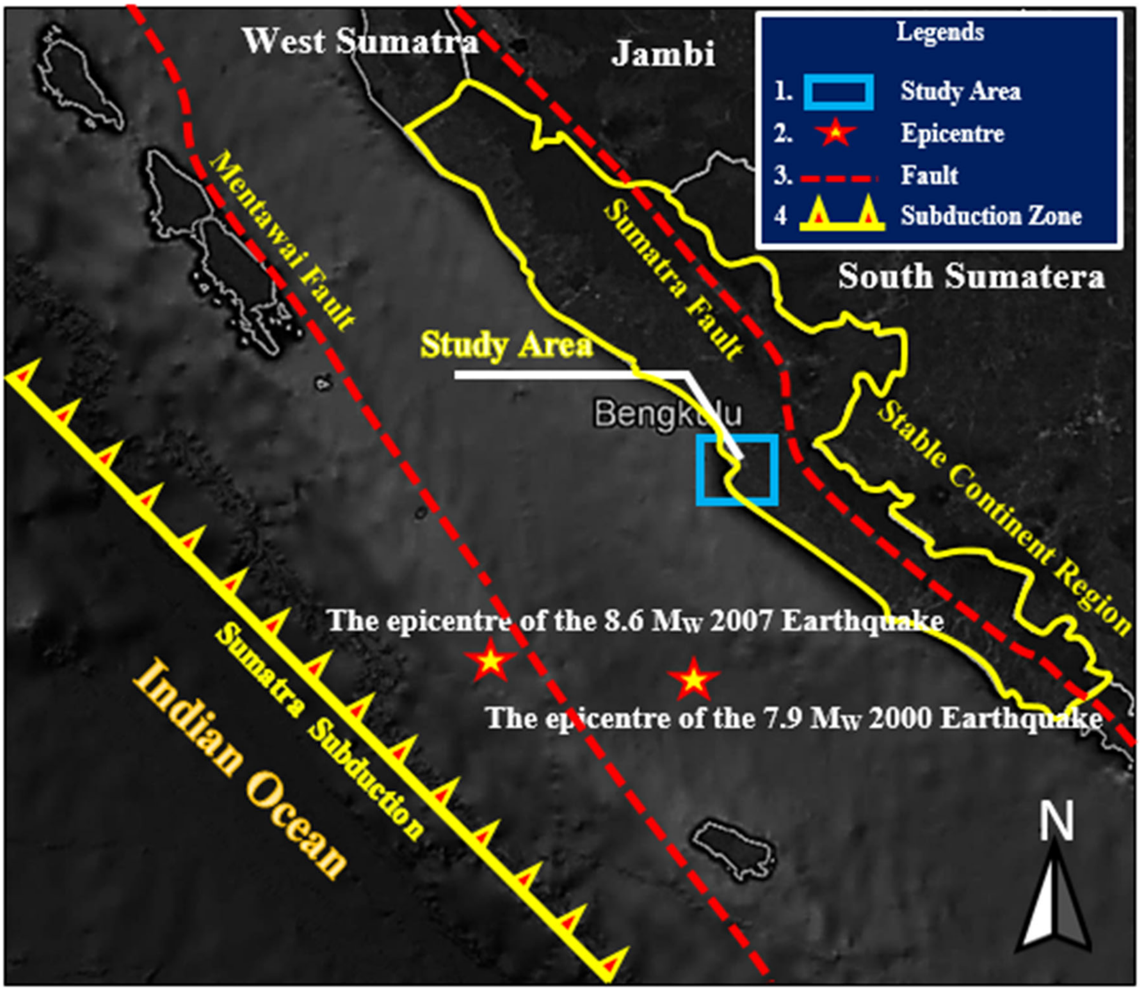

Fig. 1 Study area and seismotectonic setting of Bengkulu Province

Several studies related to the investigation of local sites in some areas have been presented. Kanli et al. [6], Long and Donohue [7], Sitharam and Anbazhagan [8], and Chakraborrty et al. [9] had implemented an active method using multichannel analysis of surface wave (MASW) to observe several areas, such as Dinar (Turkey), New Delhi (India), Oslo (Norwegia), and Jaipur (India). Furthermore, the ambient noise of microtremor, which is another well-known method, was implemented in various research, such as Mase et al. [10], Koçkar and Akgün [11], El-Hady et al. [12] to investigate Mao Lao (Thailand), Ankara (Turkey), and Marsa Alam site (Egypt). Generally, these studies concluded that both MASW and the ambient noise of microtremor are reliable methods for the investigation of local sites. Consequently, this study presents local sites investigation on the Downstream Area of Muara Bangkahulu River, Bengkulu City, Indonesia. Several geophysical measurements, including MASW and the ambient noise of microtremor, were used to determine shear wave velocity (V_s) profile in the study area. Furthermore, time-averaged shear wave velocity for the first 30 m depth (V_{s30}) was presented along with site classification based on National Earthquake Hazards Reduction Program (NEHRP) [13]. Generally, the results are able to describe the condition of local site on the downstream area of Muara Bangkahulu River. Furthermore, it serves as a reference for local government in updating spatial plan, which is based on seismic hazard mitigation in Bengkulu City.

Background of Seismic Hazards in Bengkulu City

The layout of the study area as presented in Fig. 1 shows that several earthquake sources surrounding Bengkulu City, such as Sumatra Subduction, Mentawai Fault, and Sumatra Fault. Within 20 years, at least two strong earthquakes had occurred in Bengkulu City, i.e. the M_w 7.9, which occurred on 4 June 2000 and the M_w 8.6 of 12 September 2007. They are later known as the Bengkulu-Enggano and the Bengkulu-Mentawai Earthquake, respectively. Furthermore, Farid and Mase [3] and Hausler and Anderson [14] reported that liquefaction was found during these strong earthquakes. Farid and Mase [3] also mentioned that several areas along the downstream of Muara Bangkahulu River experienced seismic impacts, such as ground failures and liquefactions during the Bengkulu-Enggano Earthquake.

Theory and Method

Study Area

The geological map of Bengkulu City is presented in Fig. 2, and its condition is composed of several formations, such as bintunan (QTb), alluvium (Qa), reef limestone (Ql), swamp deposit (Qs), alluvium terrace (Qat), and andesit (Tpan) [15]. The study area is indicated by yellow-dashed rectangular shape and it is generally composed of three dominant geological formations, namely Qat, Qa, and QTb. They are dominated by boulder, gravel, sand, silt, mud, and clay, which are mostly categorised as uncompacted materials and are sensitively scraped away by river stream [16]. Furthermore, Tsukamoto et al. [17] mentioned that saturated loose sands along river bank on the downstream area are relatively sensitive to undergo liquefaction. In line with the characteristic of dominant materials along the downstream of Muara Bangkahulu River, it is roughly predicted that this area may become liquefied during earthquakes.

The layout of the investigation points is presented in Fig. 3. In this study, MASW and microtremor measurements are performed to investigate geophysical characteristics. In addition, the geotechnical exploration was performed using cone penetration test (CPT). Generally, the study focused on Sungai Serut District, which is the subwatershed of Muara Bangkahulu Hilir. Since the area is also relatively close to the downtown, many settlements in Bengkulu City are found along the subwatershed of Muara Bangkahulu Hilir [18].

Geophysical Measurements

The Passive Method

The passive method using microtremor is widely known as one of the cheapest for site investigation [10]. Its

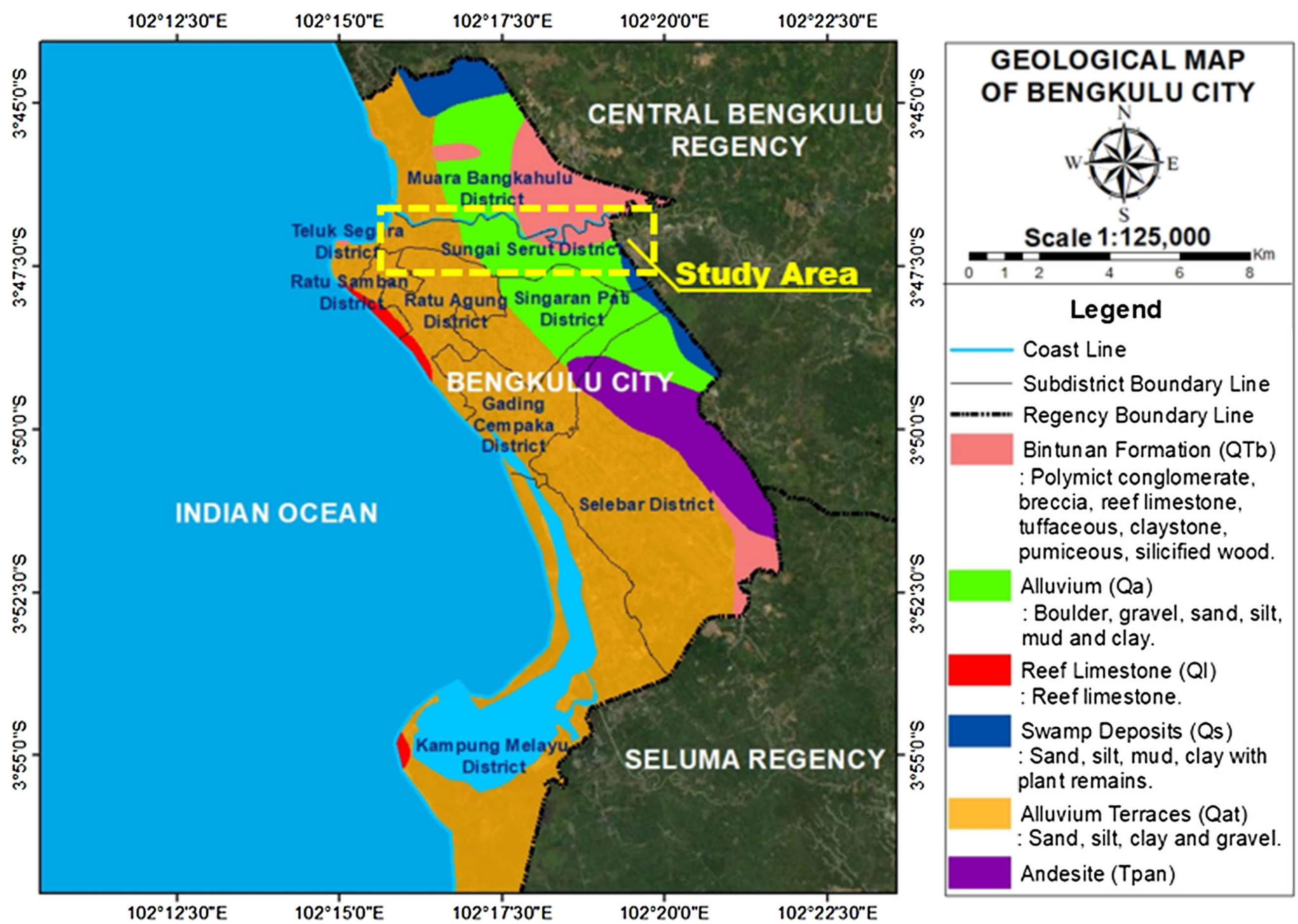

Fig. 2 Geologic map of Bengkulu City (modified from National Agency of Natural Disasters or BPBD [15])

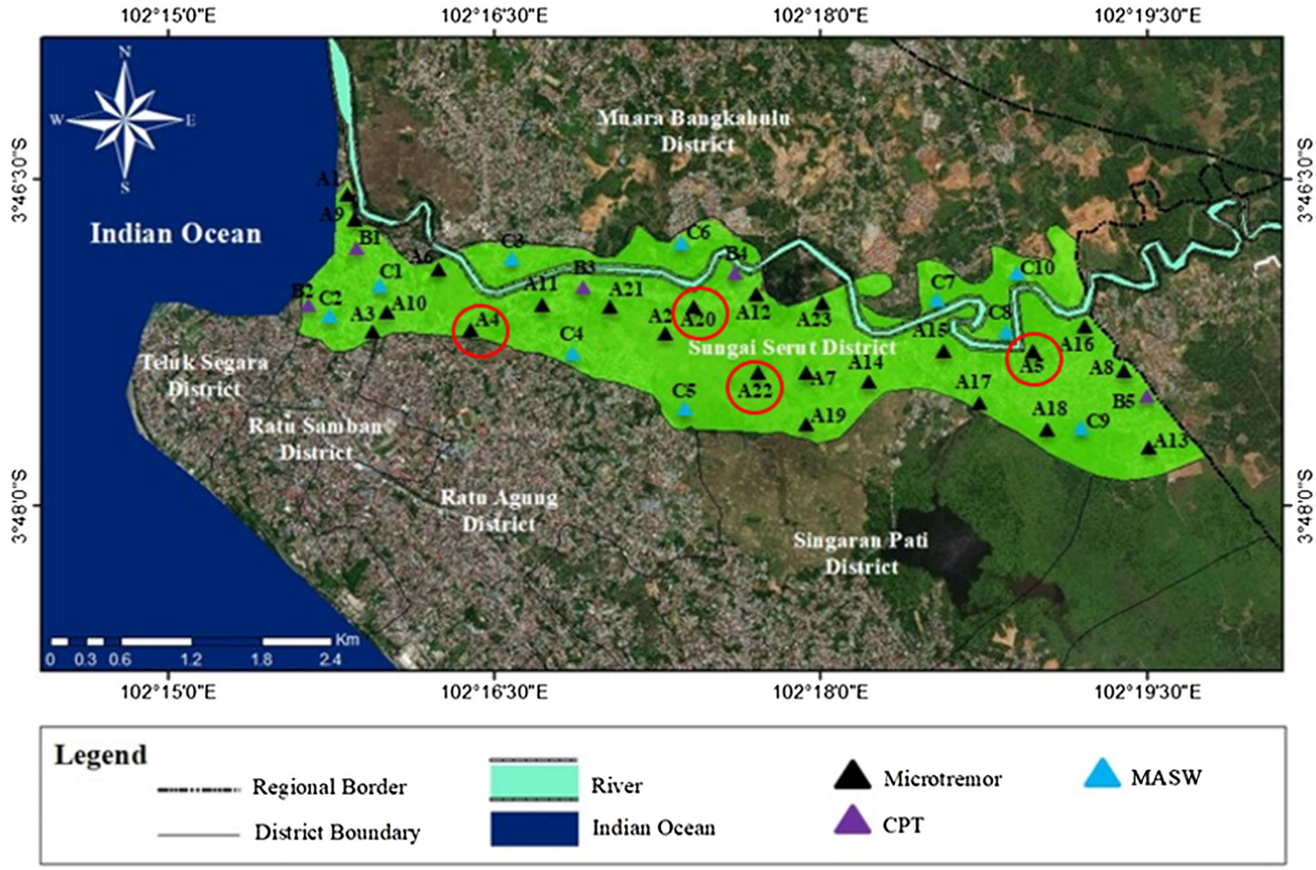

Fig. 3 Study area and site investigation locations

implementation has been presented by several researchers, such as Lachet et al. [19], Bard [20], and El-Hady et al. [12]. It was found that the main observation result is the reflection of site condition, which is interpreted into spectral ratio of horizontal motion. Kanai and Tanaka [21] introduced the technique of estimating the spectral ratio based on the observation of microtremor. This technique was later popularised by Nakamura [22], especially for geotechnical and geophysical investigations. Furthermore, Atakan [23] suggested that the spectral ratio generated by the microtremor measurement is in line with the earthquake record. Also, Lachet and Bard [24] mentioned that this method is reliable in predicting predominant frequency. The performance of spectral ratio technique has been confirmed in various research. Lachet et al. [19] and Kockar and Akgun [11] mentioned that the spectral ratios from the measurement of microtremor were more stable than the raw noise spectra. However, several effects such as human noise, the sensitivity of equipment, and environmental conditions have an effect on the result of measurement [10]. Furthermore, Bonnefoy-Clauded et al. [25] and Raptakis et al. [26] suggested that spectral ratio technique is still widely used, especially to inspect geophysical parameters.

The Active Method

Park et al. [27] introduced the active method, which is known as MASW. It was developed based on spectral analysis of surface wave (SASW) method, which is originally proposed by Nazarian et al. [28]. Furthermore, Park et al. [27] explained that MASW is useful to identify and isolate noise in accordance with the trace-by-trace coherency for arrival time and amplitude. Moreover, the difference of travel length is used to estimate the thickness of soil layer. Eikmeier et al. [29] mentioned that there are three main stages in MASW method, which include acquisition, processing, and inversion. The acquisition process is first performed to produce energy. A sledge or drop hammer is used to generate propagated seismic wave, which is then recorded by 24 geophones. The next step is processing, where the noise from field measurement is transferred into dispersion curve, which presents phase velocities versus frequency. Subsequently, the inversion technique is performed to define the best velocity model. Then, the method of stiffness matrix for layered system proposed by Kausel and Roesset [30] is employed to determine V_s profile. This process is completed once the theoretical dispersion curve is consistent with the

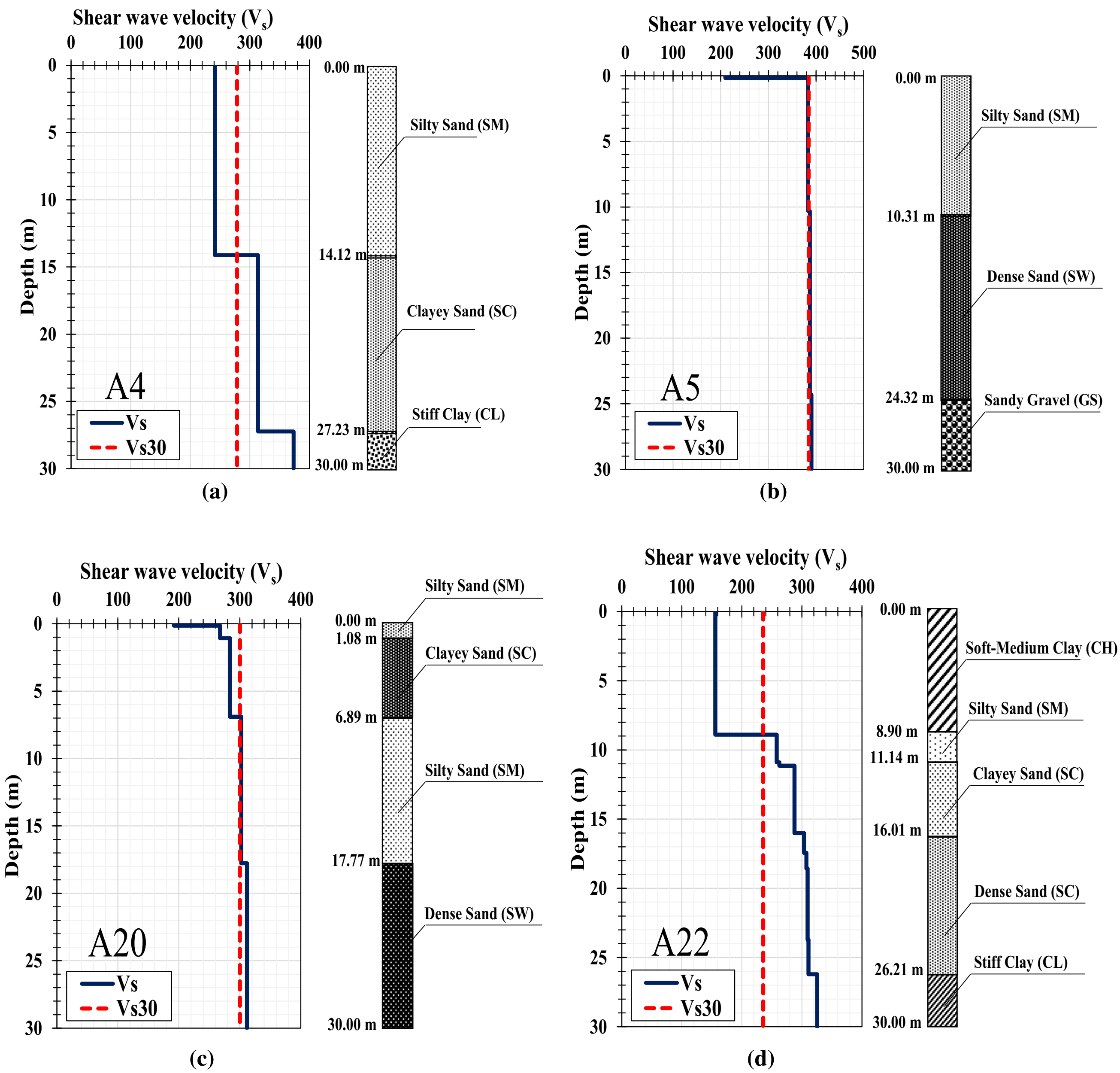

Fig. 4 Examples of measurement results **a** Site A4, **b** Site A5, **c** Site A20, and **d** Site A22

measured. Afterwards, the matched dispersion curve is then transferred into V_s profile.

Site Classification

National Earthquake Hazard Reduction Provisions (NEHRP) [12] suggested that V_{s30} is useful as the indicator to determine site classification. This system is used to determine the site-dependent seismic coefficients for earthquake–resistant design [12]. Its formulation is expressed below:

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

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

V_{s30} is generally used for specific purposes including site characterisation and response analysis. The implementation of this system is also related to ground motion prediction (GMP). Also, the updated GMP equations known as Next Generation Attenuation (NGA) models [31–35] included V_{s30}. In line with the benefit of V_{s30}, the

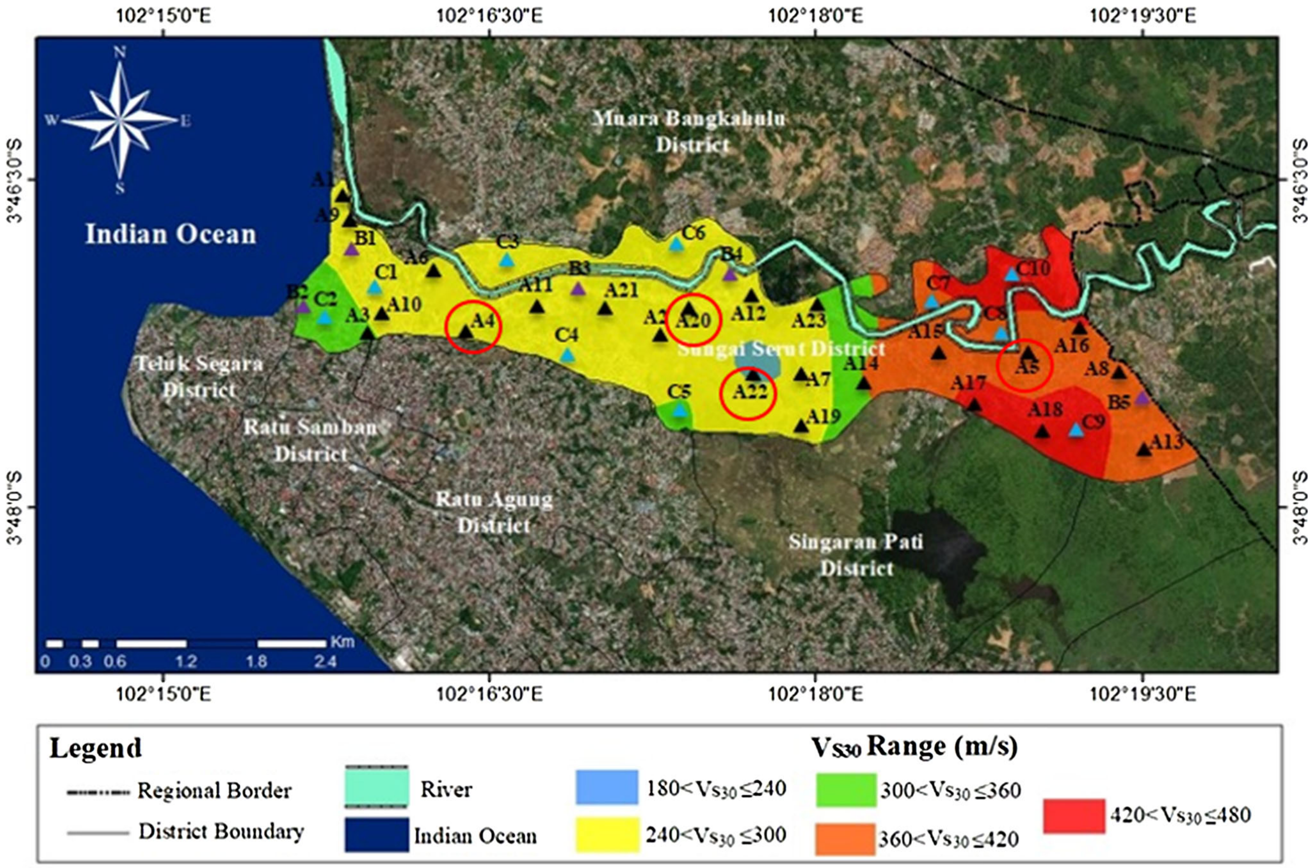

Fig. 5 Map of V_{s30} distribution in Sungai Serut District

prediction of V_s is very important for many implementations in geotechnical earthquake engineering.

Results and Discussion

Measurement Results

The results of geophysical measurements were further analysed to generate V_s profile. In this study, some representative results at A4, A5, A20, and A22, are presented in Fig. 4. A4 is located at the southern side of Muara Bangkahu River (the estuary area) and A5 at the western site. Also, A20 and A22 are located at the central side. Generally, the geological condition of these sites is relatively similar. As presented in Fig. 2, the study area is composed of Q_a and Q_{at} formations, where granular and sediment materials are dominantly found. Also, silty sand (SM) is found at shallow depth. Furthermore, the thickness is observed to vary from 1 to 14 m, with V_s of about 160 to 240 m/s. Other sand layers exist under SM, such as clayey (SC) and dense (SW), which had V_s ranging from 320 to 380 m/s. Sandy gravel (GS) is also found on certain sites, such as A5 (at depth of 24 to 30 m) with V_s of about 380 m/s/. The clay layers are generally found at A22, especially at a depth ranging from 0 to 8 m and 26 to 30 m. Generally, A4, A20, and A22 have V_s ranging from 240 to 300 m/s, therefore, these sites are categorised as Class D. Meanwhile, A5 is indicated as Class C with V_{s30} of about 384 m/s.

V_{s30} Distribution

Figure 5 presents V_{s30} map for the study area, which is divided into five ranges namely 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. Generally, these ranges of V_{s30} are derived from NEHRP [12]. However, to observe a more detailed range, the V_{s30} from NEHRP is broken down every 60 m/s. This simplified procedure was adopted by several studies, such as Silva et al. [36], Thompson and Wald [37], and Cannon and Dutta [38]. There are three dominant ranges in the study area. The first, which is V_{s30} of 240–300 m/s, is generally found on the middle to the western part. The second and the third, which are V_{s30} of 360 to 420 m/s and V_{s30} of 420 to 480 m/s, respectively are found on the eastern part of the downstream area of Muara Bangkahulu River. Based on the

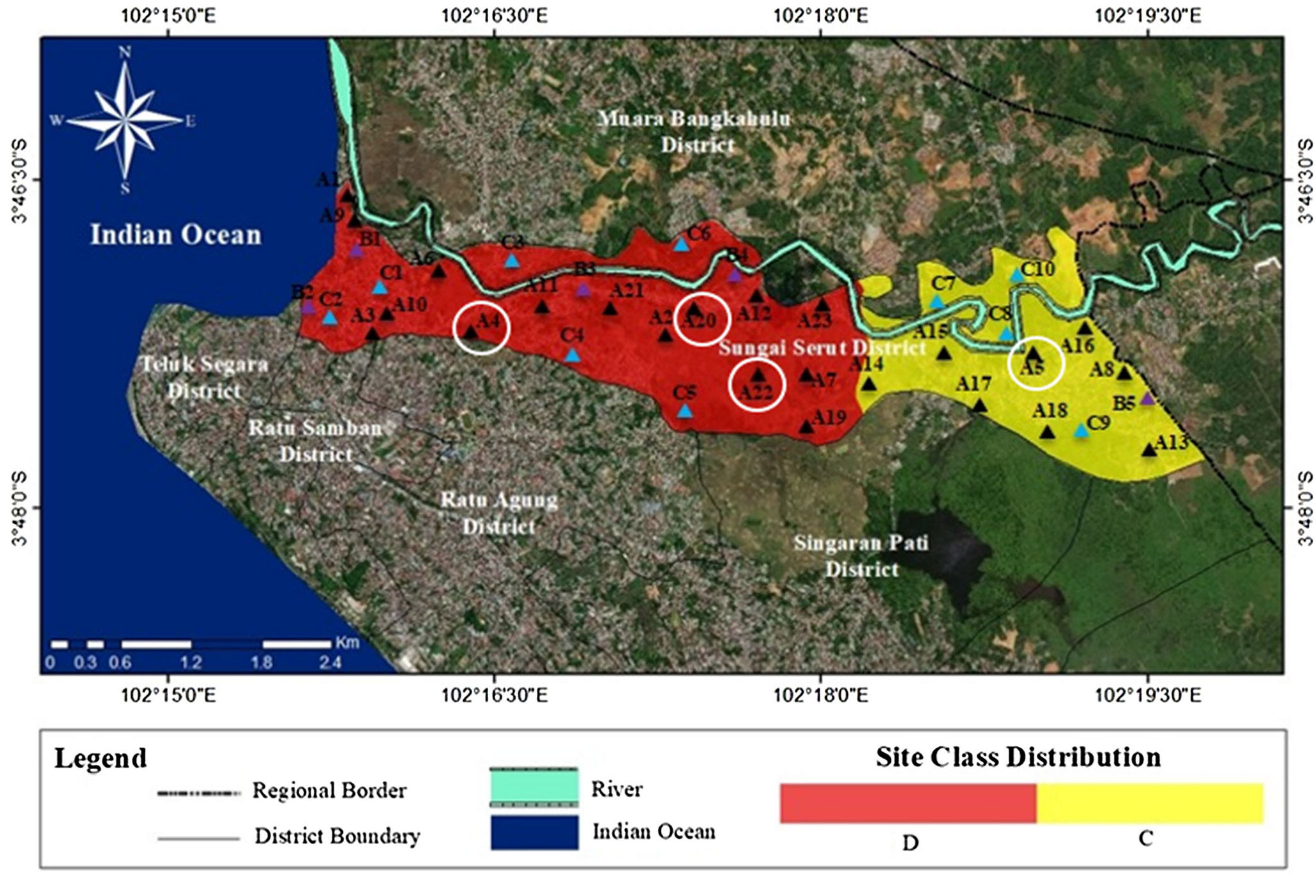

Fig. 6 Site Classification Map of Sungai Serut District

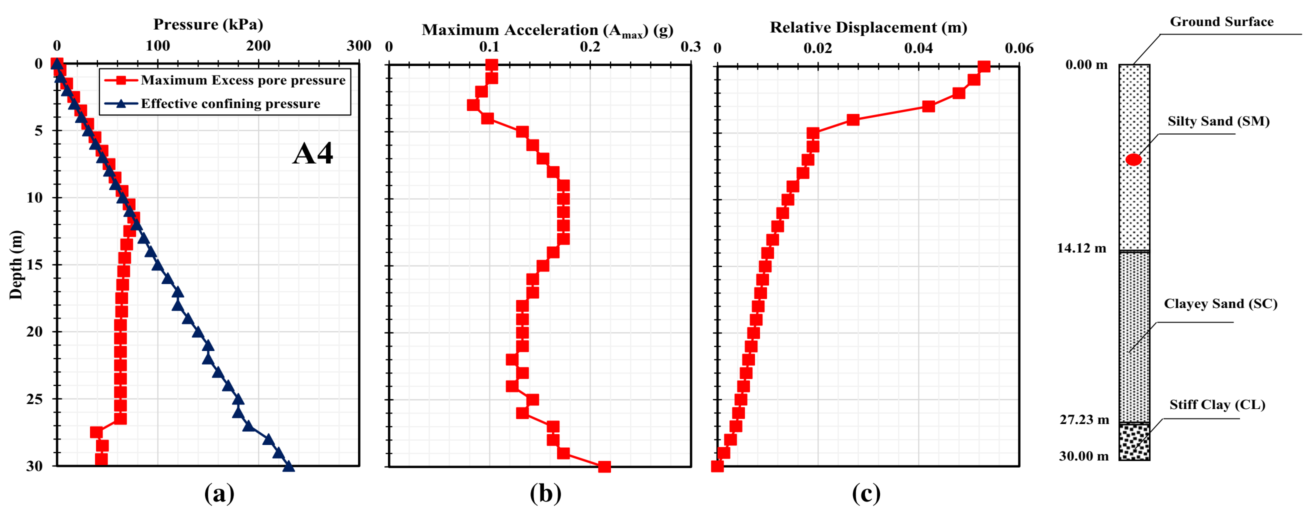

Fig. 7 Ground response profiles at A4 **a** excess pore pressure **b** maximum acceleration, and **c** relative displacement

geological map in Fig. 2, it is observed that the dominant areas are composed of alluvium terrace and deposit. These formations are made up of boulders, sands, silts, clays, and gravels, which are either loose or stiff materials with low-to-high soil resistance. Some areas which have V_{s30} of 420 to 480 m/s are composed of bintunan formation, which consists of very dense soils and soft rock materials with high density as indicated by V_s. such as conglomerate, breccia, and clay stone. There are also two small parts on middle and western parts that have V_{s30} range of about 300–360 m/s and 180–240 m/s, respectively. The area with V_{s30} of 320 to 360 m/s is composed of alluvium terrace and

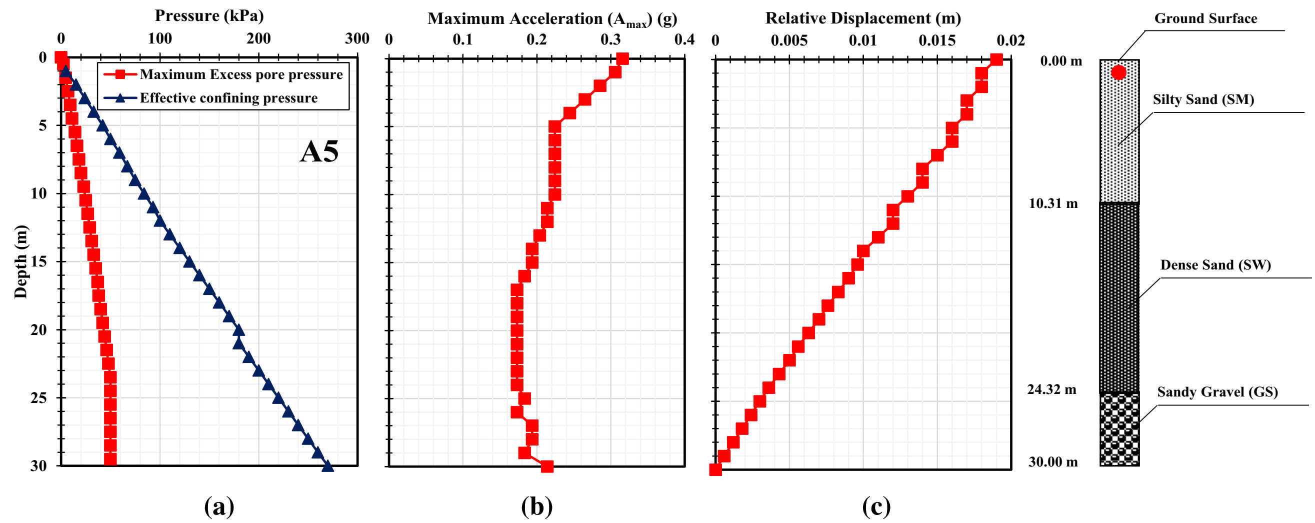

Fig. 8 Ground response profiles at A5 **a** excess pore pressure **b** maximum acceleration, and **c** relative displacement

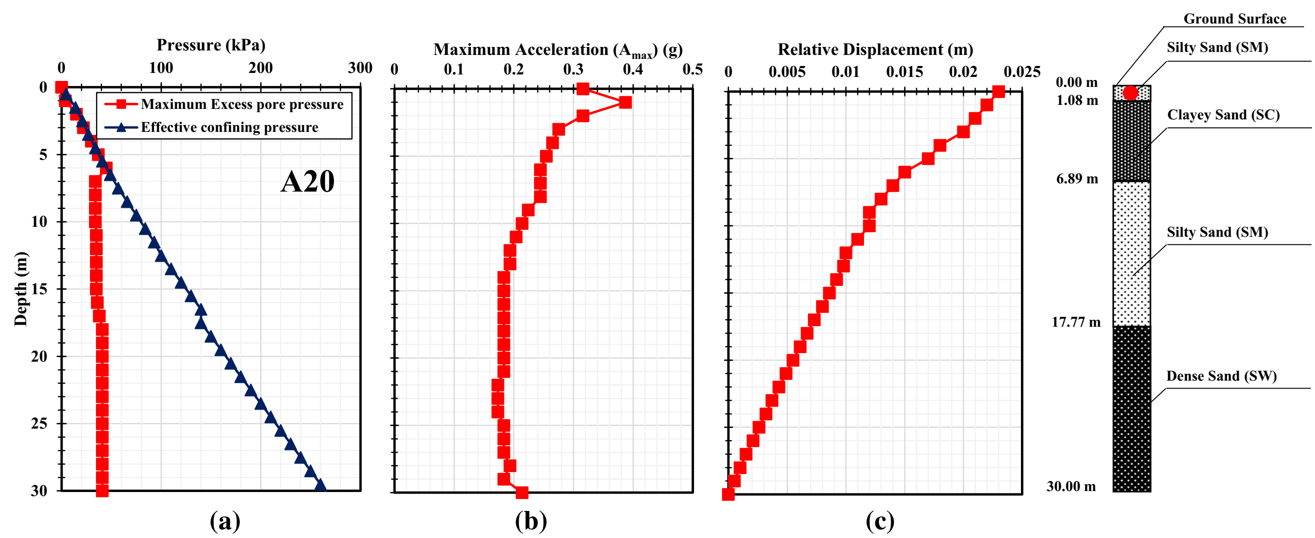

Fig. 9 Ground response profiles at A20 **a** excess pore pressure **b** maximum acceleration, and **c** relative displacement

deposit, whereas V_{s30} of 180 to 240 m/is composed of alluvium formation. In general, the distribution of V_{s30} is relatively consistent with geological formation in the study area, in which a large value indicates a large soil resistance and vice versa.

Site Classification Zonation

Figure 6 presents site classification zone for the study area, which is generated based on NEHRP [12]. The criteria had been widely used to characterise the condition of local sites for seismic ground response [39]. Furthermore, V_{s30} was implemented to predict ground motion [40]. In general, the study area consists of two main site classes, namely C and D. Class D represents areas categorised as stiff soils and C as very dense soils or soft rocks. In line with Fig. 6, Site Class C area is concentrated in middle to eastern part, whereas Site Class D is in the middle to western part. The interpretation also reveals that high-terrain area (eastern part) tends to have stiffer soil than the low (western part).

Furthermore, Wills et al. [41] mentioned that D is generally composed of holocene alluvial deposits, whereas C consists of cretaceous sedimentary rocks and coarse-grained materials. In line with the geological condition of Bengkulu City, the statement of Wills et al. [41] seems to be consistent with the finding, i.e. Site Class D is generally composed of Q_a and Q_{at}. These formations are made up of several uncompacted materials, such as loose sands, silts, and soft clays. Along the downstream area of Muara Bangkahulu River, levee units are mostly dominated by fine grain sediments which have low V_{s30}. Therefore, soil resistances are relatively low. Conversely, Site Class C is

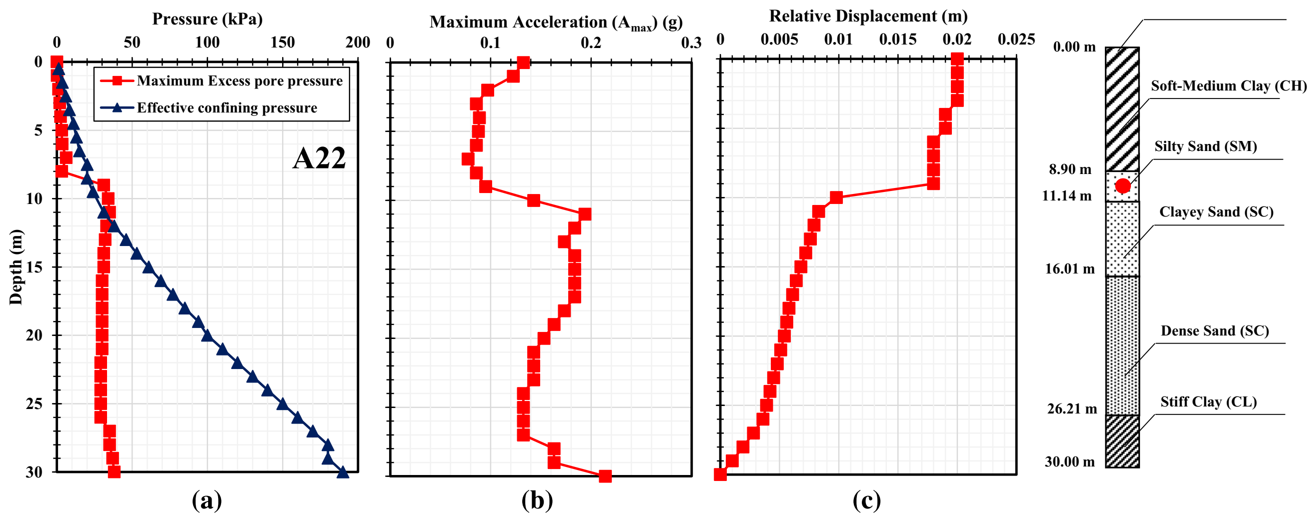

Fig. 10 Ground response profiles at A22 **a** excess pore pressure **b** maximum acceleration, and **c** relative displacement

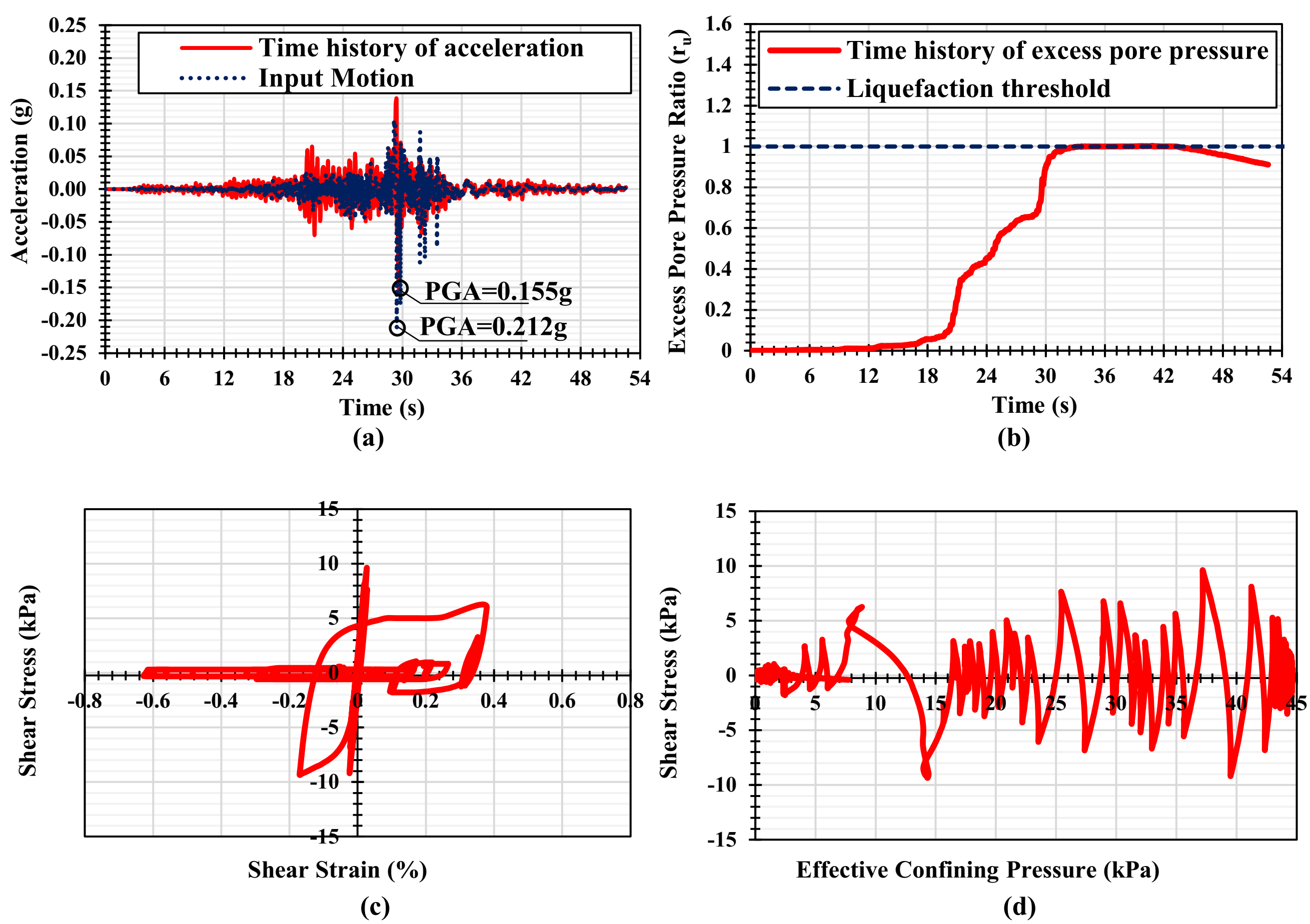

Fig. 11 Soil behaviour at A4 **a** time history of acceleration, **b** time history of excess pore pressure, **c** shear stress vs shear strain, and **d** effective stress path

generally composed of QT_b and Q_a formations which have a higher soil resistance. In addition, Kockar et al. [42] mentioned that C and D are composed of fluvial deposits, such as alluvial. Therefore, C is also found on alluvium deposits (Q_a). Thitimakorn and Chanoo [43] mentioned that a site with lower V_{s30} experiences more ground

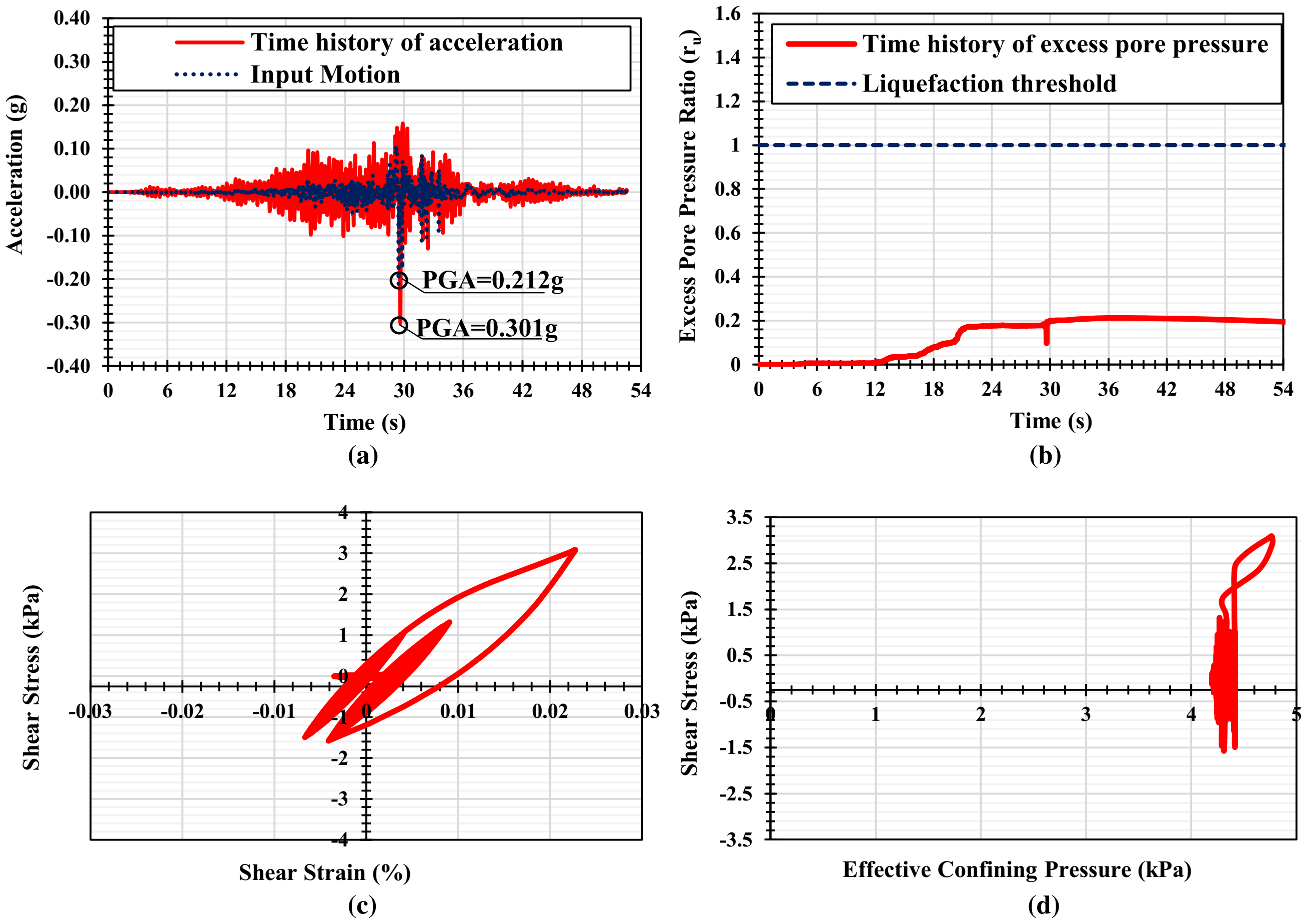

Fig. 12 Soil behaviour at A5 **a** time history of acceleration, **b** time history of excess pore pressure, **c** shear stress vs shear strain, and **d** effective stress path

shaking than those with higher V_{s30}. This indicates that the study area undergoes ground shaking impact during earthquakes. It is also concluded that the sites located at low terrain of downstream area experiences more seismic damage. Overall, the results imply that the low terrain area is relatively more vulnerable to seismic hazard. Furthermore, environmental settings and soil characteristics contribute to the control of the possible impact of seismic hazards in the study area. However, as elaborated by Putrie et al. [5], this area is still becoming the most preferred residential location in Bengkulu City.

Potential Seismic Impact

The response framework of the nonlinear seismic ground proposed by Elgamal et al. [44] is implemented to investigate soil behaviour at representative sites (A4, A5, A20, and A22). According to Misliniyati et al. [45], this method is also known as nonlinear effective stress model, which is originally derived from multi-yield surface plasticity that emphasises permanent shear strain. The benefit of this model lies on the evaluation of stiffness on each incremental step. Furthermore, the nonlinearity is simulated by plasticity increment, which is able to calculate the estimation of permanent deformation and generate soil behaviour. Several researchers, including Tonuk and Ansal [46], Pender et al. [47], and Vivek and Mohanty [48], mentioned that the method is reliable in estimating soil behaviour during earthquakes. Also, Likitlersuang et al. [49] stated that the framework of nonlinear seismic ground response is implemented to investigate soil response during remote earthquakes. Mase et al. [50] revealed that the soil deformations and behaviours from nonlinear effective stress model are generally consistent with field evidences from the 2011 Tarlay Earthquake in Northern Thailand. In this study, the ground motion of Bengkulu-Mentawai Earthquake in 2007, which is noted as the most significant in the city from Mase [1], was used as input motion. Therefore, it is realistic to consider the most significant earthquake for the ground response analysis in the study area.

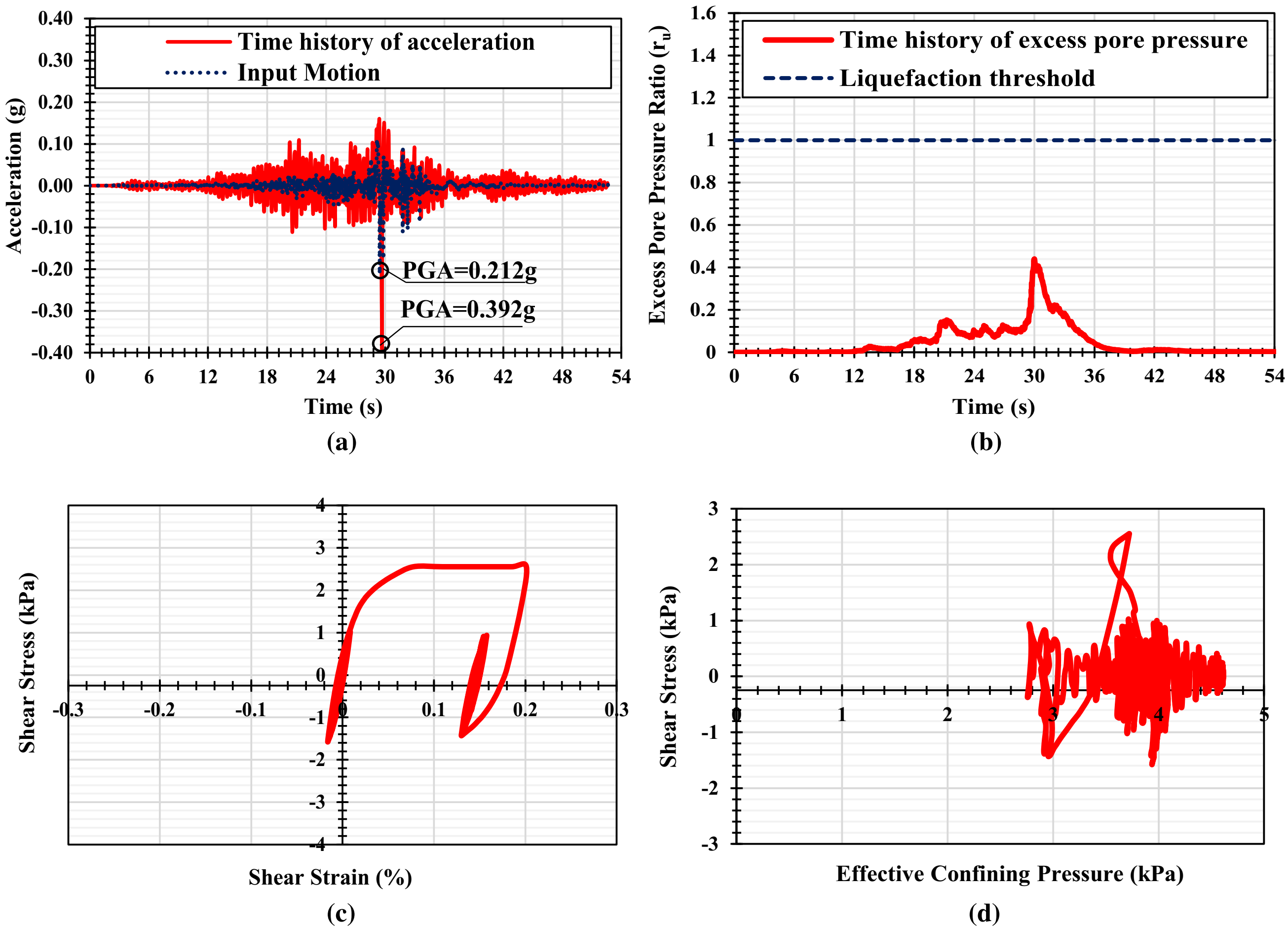

Fig. 13 Soil behaviour at A20 **a** time history of acceleration, **b** time history of excess pore pressure, **c** shear stress vs shear strain, and **d** effective stress path

Figures 7, 8, 9, and 10 present the results of ground response analysis using a nonlinear effective stress model. Furthermore, the response profile during seismic wave propagation on each site is presented. Also, three observed parameters were presented including maximum acceleration, pore pressure, and relative displacement. Generally, several sites, including A4 (Fig. 7), A20 (Fig. 9), and A22 (Fig. 10) show that excess pore exceeded effective confining pressure, especially for silty sand (SM) layer at shallow depth. However, when this happened on a soil mass, it will result in liquefaction [50]. Mase et al. [51] also mentioned that the mixture of sandy and fine soils (SM and SC) also undergo liquefaction. Therefore, it was predicted that these sites may undergo liquefaction during the Bengkulu-Mentawai Earthquake in 2007. Furthermore, several sites, such as A5 (Fig. 8) and A20 may also undergo amplification during seismic wave propagation. For others (A4 and A22), motion tends to decrease at the ground surface. This implies that there is deamplification phenomenon. Also, maximum acceleration is generally observed to vary from 0.1 g to 0.3 g at ground surface. According to Kramer [52], a minimum acceleration of 0.1 g is required to trigger liquefaction. Perhaps, this is why liquefaction occurred at several observed sites during the Bengkulu-Mentawai Earthquake in 2007. Also, the maximum relative displacement at the ground surface is observed to vary from 2 cm to 6 cm.

To observe soil behaviour on each observed site, some certain points indicated by red circles in Figs. 7, 8, 9, and 10 were selected based on the depth at which the excess pore water has exceeded the effective confining pressure. For A4, the representative point is at depth of 7.06 m, which is the mid-point of SM layer. For A5, the point is at depth of 1 m, A20 is at 0.54 m (mid-point of SM layer), and A22 at 10.02 m (mid-point of SM layer). Furthermore, soil behaviours, such as time history of acceleration, time history of excess pore pressure ratio (r_u), hysteresis loop (shear stress-shear strain), and effective stress path on representative points as presented in Figs. 11, 12, 13, and 14. It was also observed that A5 (Fig. 12) and A20 (Fig. 13) tend to undergo amplification. On the other hand, A4 (Fig. 11) and A22 (Fig. 14) tend to undergo

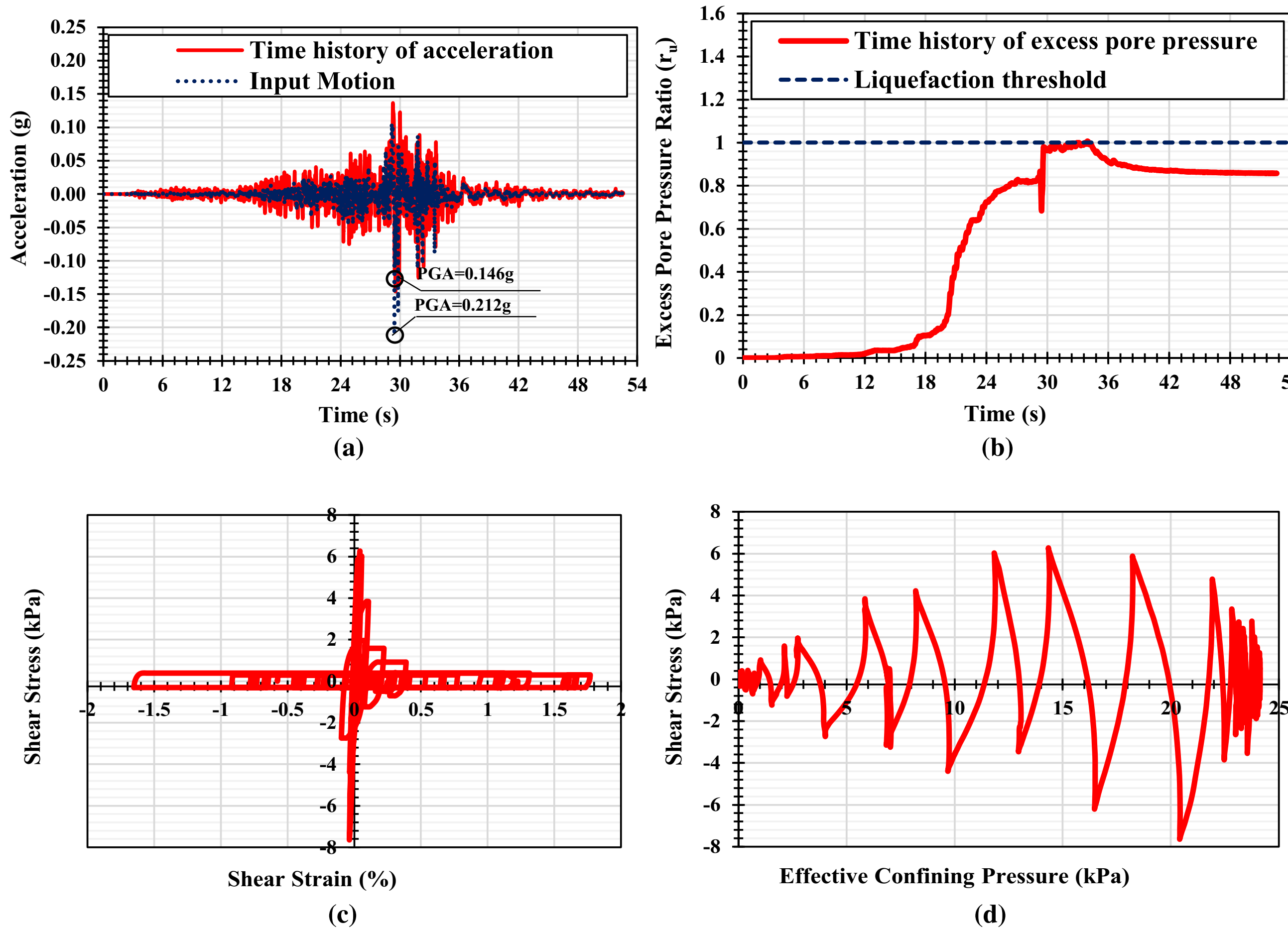

Fig. 14 Soil behaviour at A22 **a** time history of acceleration, **b** time history of excess pore pressure, **c** shear stress vs shear strain, and **d** effective stress path

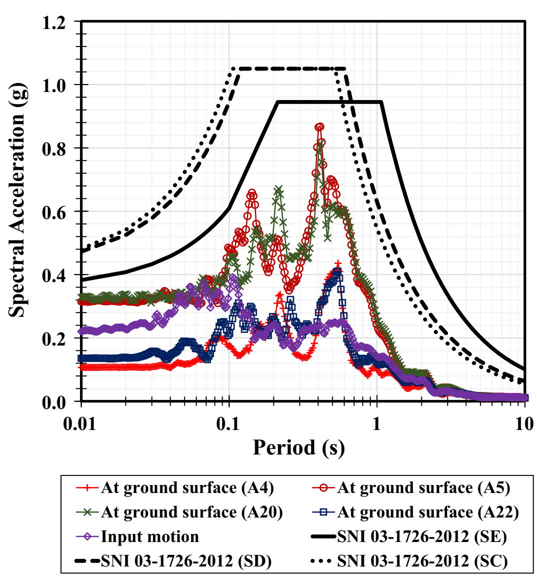

Fig. 15 Spectral accelerations comparison

deamplification. In addition, liquefaction was confirmed at various sites including A4 and A20 during seismic wave propagation. This was proven by the excess pore pressure ratio (r_u) that exceeded liquefaction threshold ($r_u \approx 1$). Based on soil profiles presented in Figs. 7, 8, 9, and 10, SM layers on both sites are indicated to undergo liquefaction. For others (A5 and A22), there is no liquefaction indication ($r_u \leq 1$). Figures 11, 12, 13, and 14 also reveal that hysteresis loop (shear stress-shear strain) varies on each observed point. For example, site A4 and A20 show the irregular hysteresis loop. The curve tends to be more flattered, which indicates a significant reduction in shear modulus due to excess pore water pressure. In addition, the effective confining pressure also decreases during seismic wave propagation. This indicates a loss of shear strength due to excess pore pressure. For A5 and A20, the hysteresis loops show that there is no flattered tendency during seismic wave propagation. Furthermore, effective stress paths show that effective confining pressure is not significantly reduced during seismic wave propagation. The time history of excess pore water pressure ratio also shows that there is no liquefaction indication on both A5 and A20 since the ratio did not exceed the threshold.

Figure 15 presents a comparison of the spectral accelerations on the ground surface to seismic design code of Bengkulu City [53]. It was observed that spectral accelerations on each represented site are relatively lower than the designs. Furthermore, when the structural buildings are built based on the seismic design code, the damage experienced during earthquakes is minimised. Several studies performed by Misliniyati et al. [13] and Hausler and Anderson [14] confirmed that there was moderate to high structural damage found along the downstream area of Muara Bangkahulu City in 2007. However, the concern about soil damage should be prioritised to minimise the impact. This is because the results show a potentially liquefiable layer at shallow depth. Therefore, it is important to perform a more in-depth study focusing on the liquefaction potential along the downstream area of Muara Bangkahulu River.

Conclusion

This study presents a local site investigation and ground response analysis on the downstream area of Muara Bangkahulu River, Bengkulu City, Indonesia. Furthermore, geophysical measurements were carried out to interpret the geological condition and geophysical characteristics of the study area. V_{s30} and site classification maps were also presented. In addition, the response analysis of seismic ground was conducted to observe soil behaviour and potential damage. In line with the above, the following concluding remarks were drawn:

(a) The geophysical interpretation of the downstream area of Muara Bangkahulu River is successfully interpreted. The V_{s30} distribution is able to describe the tendency of soil resistance in the study area. Generally, V_{s30} on the downstream area is observed to vary from 180 to 420 m/s. It also indicates that the area is dominated by Site Classes C and D. Furthermore, areas with Class D are dominated by alluvium terrace and deposit, whereas C is dominated by bintunan formation. Both site classes also reflect that the study area is composed of stiff to very dense soils and soft rocks.

(b) Sands and clays were identified as the main materials in the study area. The main geological formation of the area, which is alluvium terrace, is composed of these materials. Furthermore, dense are generally found on bintunan formation, which are composed of rocks and boulders. Also, the study area is more vulnerable to undergo some seismic impacts, such as ground amplification and liquefaction. The observation of soil behaviour confirmed that loose sandy soils at shallow depth are vulnerable to undergo liquefaction.

(c) In terms of the design of earthquake resistance, the seismic code is still reliable to be used for structural design. Generally, the results describe the environmental settings in the study area, which is useful as a recommendation for local government in developing spatial plan based on seismic hazard mitigation in Bengkulu City.

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References

1. Mase LZ (2018) Reliability study of spectral acceleration designs against earthquakes in Bengkulu City, Indonesia. Int J Technol 9(5):910–924. https://doi.org/10.14716/ijtech.v9i5.621
2. Mase LZ (2017) Liquefaction potential analysis along coastal area of Bengkulu Province due to the 2007 Mw 8.6 Bengkulu Earthquake. J Eng Technol Sci 49(6):721–736
3. 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 Geom 18(69):199–207. https://doi.org/10.21660/2020.69.24759
4. Misliniyati R, Mase LZ, Syahbana AJ, Soebowo E (2018) Seismic hazard mitigation for Bengkulu Coastal area based on site class analysis. IOP Conf Ser Earth Environ Sci 212:1–11. https://doi.org/10.1088/1755-1315/212/1/012004
5. Puteri DM, Affandi AK, Sailah S, Hudayat N, Zawawi MK (2019) Analysis of peak ground acceleration (PGA) using the probabilistic seismic hazard analysis (PSHA) method for Bengkulu earthquake of 1900–2017 period. J Phys Conf Ser 1282(1):1–11. https://doi.org/10.1088/1742-6596/1282/1/012054
6. Kanlı AI, Tildy P, Prónay Z, Pınar A, Hermann L (2006) V_{S30} mapping and soil classification for seismic site effect evaluation in Dinar region, SW Turkey. Geophys J Int 165(1):223–235
7. Long M, Donohue S (2007) In situ shear wave velocity from multichannel analysis of surface waves (MASW) tests at eight Norwegian research sites. Can Geotech J 44(5):533–544. https://doi.org/10.1139/t07-013
8. Sitharam TG, Anbazhagan P (2008) Seismic microzonation: principles, practices and experiments. EJGE Spec Vol Bouquet 8:1–61
9. Chakrabortty P, Kumar U, Puri V (2018) Seismic site classification and liquefaction hazard assessment of Jaipur City, India. Indian Geotech J 48(4):768–779. https://doi.org/10.1007/s40098-017-0287-x
10. 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. https://doi.org/10.1080/13632469.2018.1469441
11. Koçkar MK, Akgün H (2012) Evaluation of the site effects of the Ankara basin, Turkey. Appl Geophys 83(1):120–134. https://doi.org/10.1016/j.jappgeo.2012.05.007

12. El-Hady S, Fergany EAA, Othman A, Mohamed GEA (2012) Seismic microzonation of Marsa Alam, Egypt using inversion HVSR of microtremor observations. J Seismolog 16(1):55–66. https://doi.org/10.1007/s10950-011-9249-4
13. National Earthquake Hazards Reduction Program (NEHRP) (1998) Recommended Provisions for Seismic Regulation for New Buildings and Other Structures: Part 1-Provisions and Part 2-Commentary. FEMA 302, Texas, USA
14. Hausler E, Anderson A (2007) Observation of the 12 and 13 September 2007 Earthquake, Sumatra, Indonesia. Build Change Report, Denver, Colorado, USA
15. Natural Disaster Agency of Bengkulu Province (BPBD) (2018) Geological map of Bengkulu City, Indonesia. Natural Disaster Agency of Bengkulu Province (BPBD), Bengkulu, Indonesia
16. Sadeghi SH, Gharemahmudli S, Kheirfam H, Darvishan AK, Harchegani MK, Saeidi P, Vafakhah M (2018) Effects of type, level and time of sand and gravel mining on particle size distributions of suspended sediment. Int Soil Water Conserv Res 6(2):184–193. https://doi.org/10.1016/j.iswcr.2018.01.005
17. Tsukamoto Y, Kawabe S, Kokusho T (2012) Soil liquefaction observed at the lower stream of Tonegawa river during the 2011 off the Pacific Coast of Tohoku Earthquake. Soils Found 52(5):987–999. https://doi.org/10.1016/j.sandf.2012.11.016
18. Putrie NS, Susiloningtyas D, Pratami M (2019) Distribution pattern of settlement in 2032 based on population density in Bengkulu City. IOP Conf Ser Earth Environ Sci 284(1):1–8. https://doi.org/10.1088/1755-1315/284/1/012007
19. Lachet C, Hatzfeld D, Bard PY, Theodulidis N, Papaioannon C, Savaidis A (1996) Site effect and microzonation in the City of Thessaloniki (Greece): comparison of different approaches. Bull Seismological Soc Am 86(1):1703–1962
20. Bard PY (2004) The SESAME-FP5 project: an overview and main results. In: Proceedings of the 13th world conference on earthquake engineering, 1–6 August, Vancouver, Canada
21. Kanai K, Tanaka T (1954) Measurement of the microtremor. Bull Earthq Res Inst 32(1):199–209
22. Nakamura Y (1989) A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface. Railway Techn Res Inst Quart Rep 30(1):25–33
23. 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) Proceedings 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
24. Lachet C, Bard PY (1994) Numerical and theoretical investigations on the possibilities and limitations of Nakamura's technique. Phys Earth 42(1):377–397. https://doi.org/10.4294/jpe1952.42.377
25. Bonnefoy-Claudet S, Cornou C, Bard PY, Cotton F, Moczo P, Kristek J, Fah D (2006) H/V ratio: a tool for site effects evaluation, results from 1-D noise simulations. Geophys J Int 167(2):827–837. https://doi.org/10.1111/j.1365-246X.2006.03154.x
26. Raptakis DG, Manakou MV, Chávez-García FJ, Makra KA, Pitilakis KD (2005) 3D configuration of Mygdonian basin and preliminary estimate of its site response. Soil Dyn Earthq Eng 25(11):871–887. https://doi.org/10.1016/j.soildyn.2005.05.005
27. Park CB, Miller RD, Xia J (1999) Multichannel analysis of surface waves. Geophysics 64(3):800–808. https://doi.org/10.1190/1.1444590
28. Nazarian S, Stokoe II, Kenneth H, Hudson WR (1983) Use of spectral analysis of surface waves method for determination of moduli and thicknesses of pavement systems. Transp Res Rec 930:38–45
29. Eikmeier CN, Prado RL, Taioli F (2016) Combined use of active and passive surface waves for shallow subsurface investigation in noisy urban area of São Paulo City, Brazil. Braz J Geophys 34(1):13–24
30. Kausel E, Roesset JM (1981) Stiffness matrices for layered soils. Bull Seismological Soc Am 71(6):1743–1761
31. Abrahamson NA, Silva WJ, Kamai R (2014) Summary of the ASK14 ground motion relation for active crustal regions. Earthq Spectra 30(3):1025–1055. https://doi.org/10.1193/070913EQS198M
32. Boore DM, Stewart JP, Seyhan E, Atkinson GM (2014) NGA-West2 equations for predicting PGA, PGV, and 5% damped PSA for shallow crustal earthquakes. Earthq Spectra 30(3):1057–1085. https://doi.org/10.1193/070113EQS184M
33. Campbell KW, Bozorgnia Y (2014) NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra. Earthq Spectra 30(3):1087–1115. https://doi.org/10.1193/062913EQS175M
34. Chiou BSJ, Youngs RR (2014) Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra. Earthq Spectra 30(3):1117–1153. https://doi.org/10.1193/072813EQS219M
35. Idriss IM (2014) An NGA-West2 empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. Earthq Spectra 30(3):1155–1177. https://doi.org/10.1193/070613EQS195M
36. Silva V, Crowley H, Varum H, Pinho R (2015) Seismic risk assessment for mainland Portugal. Bull Earthq Eng 13(2):429–457. https://doi.org/10.1007/s10518-014-9630-0
37. Thompson EM, Wald DJ (2012). Developing V_{S30} site-condition maps by combining observations with geologic and topographic constraints. In: Proceedings of the 15th world conference on earthquake engineering, 24–28 September, Lisbon, Portugal
38. Cannon EC, Dutta U (2015) Evaluating topographically-derived V_{s30} values for seismic site class characterization in Anchorage, Alaska, USA. In: Proceedings of the 6th international conference on earthquake geotechnical engineering, 2–4 November, Christchurch, New Zealand
39. McPherson A, Hall L (2013) Site classification for earthquake hazard and risk assessment in Australia. Bull Seismol Soc Am 103(2A):1085–1102. https://doi.org/10.1785/0120120142
40. Mase LZ, Likitlersuang S, Tobita T (2018) Analysis of seismic ground response caused during strong earthquake in Northern Thailand. Soil Dyn Earthq Eng 114(11):113–126. https://doi.org/10.1016/j.soildyn.2018.07.006
41. Wills CJ, Petersen M, Bryant WA, Reichle M, Saucedo GJ, Tan S, Treiman J (2000) A site-conditions map for California based on geology and shear-wave velocity. Bull Seismol Soc Am 90(6B):S187–S208. https://doi.org/10.1785/0120000503
42. Koçkar MK, Akgün H, Rathje EM (2008) Evaluation of site conditions for the Ankara Basin of Turkey based on seismic site characterization. In: Proceedings of the 14th world conference on earthquake engineering, 12–17 October, Beijing, China
43. Thitimakorn T, Channoo S (2012) Shear wave velocity of soils and NEHRP site classification map of Chiangrai city, Northern Thailand. Electron J Geotech Eng 17:2891–2904
44. Elgamal A, Yang Z, and Lu J (2006) Cyclic1D: a computer program for seismic ground response. Report No. SSRP-06/05, Department of Structural Engineering, University of California, San Diego, La Jolla, California, USA
45. Misliniyati R, Mase LZ, Irsyam M, Hendriawan H, Sahadewa A (2019) Seismic response validation of simulated soil models to vertical array record during a strong earthquake. J Eng Technol Sci 51(6):772–790. https://doi.org/10.5614%2Fj.eng.technol.sci.2019.51.6.3

46. Tönük G, Ansal A (2008) Effects of stress reduction factors on liquefaction analysis. In: Congress of geotechnical earthquake engineering and soil dynamics IV, 1–10, May 18-22, Sacramento, USA. https://doi.org/10.1061/40975(318)66
47. Pender MJ, Orense RP, Wotherspoon LM, Storie LB (2016) Effect of permeability on the cyclic generation and dissipation of pore pressures in saturated gravel layers. Geotechnique 66(4):313–322. https://doi.org/10.1680/jgeot.SIP.15.P.024
48. Vivek BS, Mohanty S (2016) 1D Ground Response Analysis of Bhubaneswar Soil in India. In: Proceedings of the 6th international conference on recent advances in geotechnical earthquake engineering and soil dynamics, August 1–6, 2016, Greater Noida, India
49. Likitlersuang S, Plengsiri P, Mase LZ, 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. https://doi.org/10.1007/s10064-019-01560-9
50. Mase LZ (2017) Shaking table test of soil liquefaction in Southern Yogyakarta. Int J Technol 8(4):747–760. https://doi.org/10.14716/ijtech.v8i4.9488
51. Mase LZ, Likitlersuang S, Tobita T (2019) Cyclic behaviour and liquefaction resistance of Izumio sands in Osaka, Japan. Mar Georesour Geotechnol 37(7):765–774. https://doi.org/10.1080/1064119X.2018.1485793
52. Kramer SL (1996) Geotechnical earthquake engineering. Prentice Hall, New Jersey
53. SNI 03-1726-2012 (2012) Standard of earthquake resistance design for building. National Standardization Agency, Jakarta