Makara Journal of Technology

Volume 24 | Number 1 Article 6

4-1-2020

Liquefaction Potential Analysis Based on Nonlinear Ground Response on the Coastline of Bengkulu City, Indonesia

Lindung Zalbuin Mase
Department of Civil Engineering, Faculty of Engineering, Universitas Bengkulu, Bengkulu 38371, Indonesia, lmase@unib.ac.id

Recommended Citation
Mase, Lindung Zalbuin (2020) "Liquefaction Potential Analysis Based on Nonlinear Ground Response on the Coastline of Bengkulu City, Indonesia," *Makara Journal of Technology*: Vol. 24 : No. 1 , Article 6.
DOI: 10.7454/mst.v24i1.3778
Available at: https://scholarhub.ui.ac.id/mjt/vol24/iss1/6

Makara J. Technol. 24/1 (2020), 34–42
doi: 10.7454/mst.v24i1.3778

Liquefaction Potential Analysis Based on Nonlinear Ground Response on the Coastline of Bengkulu City, Indonesia

Lindung Zalbuin Mase

Department of Civil Engineering, Faculty of Engineering, Universitas Bengkulu, Bengkulu 38371, Indonesia

e-mail: lmase@unib.ac.id.

Abstract

This paper presents the study of the seismic response and liquefaction potential of the coastal area of Bengkulu City during the September 2007 Sumatra earthquake. The study is conducted by collecting site investigation data (standard penetration test) and applying input motion to observe soil response. Synthetic ground motion is generated by considering the important aspects of earthquakes, including focal depth, epicenter, earthquake source, and site classification. The synthetized ground motion is then used as the input motion in the seismic response analysis. The results of this analysis are spectral acceleration and peak ground acceleration at each depth. The resulting spectral acceleration is compared with that specified in the seismic design code of Indonesia (SNI 03-1726-2012). Liquefaction potential analysis is performed on the basis of the results of the seismic response analysis. Results show that spectral acceleration depends on soil type. A high soil density equates to a low spectral response. The designed spectral acceleration may still be considered for each borehole, especially for T (period) < 1. However, for T > 1, spectral acceleration should be prioritized, especially for high-rise building construction. The liquefaction analysis reveals that a shallow depth is vulnerable to liquefaction. In general, this study could give a better understanding on the implementation of seismic ground response for liquefaction potential analysis.

Abstrak

Potensi Likuifaksi Berdasarkan Response Tanah Nonlinear pada Area Pesisir Kota Bengkulu, Indonesia. Naskah ini menyajikan studi respon seismic dan potensi likuifaksi pada area pesisir Kota Bengkulu akibat Gempa Sumatra September 2007. Studi ini dilakukan dengan mengumpulkan data investigasi lapangan berupa data penetrasi standard dan menerapkan perambatan gelombang untuk mengamati bagaimana respon tanah. Gelombang sintetis dihasilkan dengan mempertimbangan aspek penting kegempaaan, seperti kedalaman, jarak episenter, sumber gempa, dan klasifikasi kelas situs. Gelombang sintetis selanjutnya digunakan sebagai input pada analisis respon seismik. Hasil analisis ini adalah percepatan spektra dan percepatan gelombang gempa pada setiap kedalaman. Percepatan spektra hasil perambatan gelombang seismik selanjutnya dibandingkan dengan SNI 03-1726-2012. Analisis potensi likuifaksi juga dilakukan berdasarkan hasil analisis respon seismik. Hasil penelitian ini menunjukkan bahwa percepatan spektra bergantung pada jenis tanah. Semakin tinggi kepadatan tanah maka percepatan spektra semakin rendah. Spektra desain masih dapat diterapkan untuk setiap lokasi yang di studi, khususnya untuk perioda (T) kurang dari satu. Meskipun demikian untuk T > 1 detik, percepatan spektra harus diutamakan, khususnya untuk bangunan berlantai tinggi. Analisis likuifaksi juga menjelaskan bahwa likuifaksi dapat terjadi pada kedalaman dangkal. Secara umum, hasil penelitian ini dapat memberikan pemahaman yang lebih baik mengenai implementasi respon gelombang seismik untuk analisis potensi likuifaksi.

Keywords: wave propagation; earthquake; liquefaction potential, Bengkulu City

1. Introduction

On September 12, 2007, an earthquake with a magnitude of 8.6 M_w struck Bengkulu Province and its surrounding areas. According to the Meteorological, Climatological, and Geophysical Agency (locally known as “Badan Meteorologi, Klimatologi dan Geofisika or BMKG), the earthquake caused major destruction, especially in Bengkulu City, the capital city of Bengkulu Province [1]. BMKG [1] also reported that the damage intensity was VI in the Modified Mercalli Intensity (MMI) scale. This earthquake not only caused destructive damage but also triggered the liquefaction phenomenon, particularly along the coastal area of Bengkulu City. Learning from this event, this intensive study investigates the seismic effect of the earthquake and its impact on the liquefaction potential of the coastal area of Bengkulu City.

Seismic response analysis has been widely conducted to study the effects of the wave propagation of earthquakes. In 1972, an analysis method using an equivalent linear approach to the one-dimensional wave propagation of layered soils was introduced by Schnabel *et al*. [2]. This method considers soil profiles as homogenous systems with viscoelastic sublayers and semi-infinite horizontal layers. According to its history, this method was developed on the basis of either a wave equation solution, as proposed by Kanai [3], Matthiesen *et al*. [4], Roesset and Witmann [5], and Lysmer *et al*. [6]; or a lumped mass system, as proposed by Idriss and Seed [7]. Although this method has been widely applied to the seismic analysis problem, it suffers from several limitations, including the overestimation of the maximum acceleration [8] and the underestimation of the amplification ratio [9]. Nevertheless, several improvements have been made to overcome these limitations [9]. Another method for seismic response analysis was proposed by Elgamal *et al*. [10] and Yang *et al*. [11]. This method is based on nonlinear finite elements for one-dimensional seismic wave propagation. Different from the equivalent linear approach, this method was proposed to cover the effects of the nonlinearity of soil behavior.

Seismic response is closely related to liquefaction potential. Liquefaction is the loss of soil shear strength due to earthquakes. It generally occurs on uniform saturated sandy soils with very loose to moderate density. In the event of an earthquake, the wave propagation immediately triggers the loss of the shear strength of uniform sandy soils due to the excess pore water pressure. The shear strength loss can reduce the effective soil stress, which serves as the main factor that supports self-weight loads. An effective stress of zero indicates the occurrence of liquefaction and the possible formation of large settlements. Seed and Idriss [12] proposed a method for estimating the factor of safety of liquefaction (*FS*) using the equilibrium concept characterized by cyclic resistance ratio (*CRR*) and cyclic stress ratio (*CSR*). This method is usually described as conventional. The *CRR* is generated on the basis of the soil resistance obtained from site investigation information, including that from the standard penetration test (SPT) [12], cone penetration test (CPT) [13], shear wave velocity (V_s) [14], and dilatometer test [15]. The *CSR* is generated on the basis of earthquake load parameters, such as peak ground acceleration (PGA), earthquake magnitude (M_w), depth reduction (r_d), effective stress (σ_v), and total stress (σ_v').

In the present study, seismic analysis is conducted to observe the soil response resulting from the wave propagation to the soil investigation points, especially those along the coastal area of Bengkulu City. Nonlinear finite element methods are employed to cover the nonlinearity of soil behavior. The soil response, that is, the spectral acceleration, of each investigated point is compared with the spectral response of the seismic design code of the investigated area. In addition, the PGA obtained from the seismic ground analysis is used to analyze liquefaction potential. The results of this study are expected to provide a clear explanation of seismic response and its effect on soil response, especially in the context of liquefaction.

Earthquakes and Liquefaction in Bengkulu City. From 2000 to 2010, Bengkulu experienced two large earthquake events. One earthquake event occurred on June 4, 2000, and it recorded a magnitude of 7.9 M_w. Another earthquake struck on September 12, 2007, and its magnitude was 8.6 M_w. These earthquakes caused massive destruction and traumatized the people of Bengkulu. They also induced other destructive events, such as liquefactions, landslides, and ground failures. Liquefaction occurred in 2000 and 2007, and it has been attracting the attention of local researchers studying earthquakes and liquefaction potential, especially along coastal areas that are dominated by sandy soils. Mase [16] studied the characteristics of the earthquakes that struck Bengkulu City in 2000–2010. This study also considered the MMI scales of the two large earthquake events that occurred in the last decade. These earthquakes reached the maximum MMI scales of VIII and XI. Mase [17] conducted liquefaction research in a coastal area in Bengkulu City using a conventional method. The study showed that several areas along the coastline of Bengkulu City, such as Lempuing, Anggut, and Pantai Panjang, could undergo liquefaction. Mase [18] studied the liquefaction potential along the coastal area of Bengkulu City using the one-dimensional site response analysis to observe the soil behavior of the liquefied layers. The results revealed that the sand layers at shallow depths are vulnerable to liquefaction during an earthquake. Previous studies generally focused on the implementation of either empirical analyses or numerical analyses to predict earthquake impact and liquefaction. No study has combined both methods to investigate liquefaction. Hence, the present study combines empirical and numerical analyses to investigate the liquefaction potential of the study area.

Geological Condition. Referring to previous studies, this study focuses on the coastal area of Bengkulu City. Mase [17] performed three boring logs (SPT), followed by SPT, to determine the soil resistance, soil layer, and geological condition of this area. The site investigation data of Mase [17] are used in the current work. The site investigation locations are noted as SPT-1 in Anggut

Figure 1. Layout of Site Investigation Along the Coastal Area of Bengkulu City (Modified from Google Earth [2])

subdistrict, SPT-2 in Pantai Panjang subdistrict, and SPT-3 in Lempuing subdistrict. The location of the SPT in this study is presented in Figure 1. The geological condition of the coastal area of Bengkulu City is dominated by sandy soils. A 1.5 m-thick layer of loose sandy soil with fines content (FC) of 5%–6% is found 0–1.5 m below the ground surface and 7.5–10 m below the ground surface. This sand soil is categorized as poor graded sand (SP) in the USCS classification system. Medium sand measuring 3–6 m thick is found 1.5–4.5 and 1.5–7.5 m below the ground surface. These layers have FC of 15%–18% and are classified as silty sand (SM). Dense sand with 5% FC are found 4.5–10 m deep below the surface. It is classified as well graded sand (SW). The ground water table of all the investigated areas is located near the ground surface. The site investigation along the coastal area of Bengkulu City reveals that loose sandy soil and medium sandy soil layers with a shallow ground water table are extremely vulnerable to liquefaction due to earthquakes. These layers were liquefied during the earthquake on September 12, 2007 [17]. The water table of each borehole found at shallow depths is another main factor that potentially induced the liquefaction in 2007. If sandy layers with a low water table depth are shaken by an earthquake, then excess pore water pressure builds up. Effective soil stress can also drop to zero. Under such conditions, liquefaction is likely to occur.

2. Methods

A site investigation was carried out along the coastal area of Bengkulu City. Shallow SPT and soil sampling were conducted on the three sites. Further analysis in the laboratory was performed to determine the soil characteristics, including the physical and engineering properties. The determined soil properties were then considered as the input parameters in the simulation. Information about other major earthquakes that struck the surrounding areas of Bengkulu City was also collected. The 8.6 M_w earthquake that occurred on September 12, 2007, is regarded as the most destructive earthquake in Bengkulu City. It is considered as the controlling earthquake.

The goal of this study is to determine the effects of wave propagation on soil response. Therefore, energy in the form of ground motion must be applied to the bases of the investigation points. However, the ground motion data of the 2007 earthquake are unavailable. An alternative is synthetic ground motion. Synthetic ground motion is generated on the basis of several important factors, such as the earthquake source, distance to epicenter, depth of rupture, and site classification of the investigated point. These parameters can be obtained from BMKG [1].

The estimated PGA of 0.275 g at the bedrock of Bengkulu City was obtained from the work of Mase [18]. This value was used to generate synthetic ground motion. Ground motion was synthetized with SeismoArtif 19]. This software considers earthquake parameters such as earthquake mechanism, magnitude, and distance to rupture. Mase [18] recommended the 8.6 M_w earthquake that occurred on September 12, 2007 as the controlling earthquake of Bengkulu City. Therefore, the earthquake parameters of the study were used to generate the synthetic ground motion in the current work (Figure 3).

The synthetized ground motion was then applied to the bases of the investigation points in the study area (Figure 2) using one-dimensional nonlinear seismic ground response analysis. The bottom of a borehole was assumed as an elastic half-space surface. This assumption was based on the work of Gafoer *et al*. [20], who stated that the study area is dominated by sand underlain by reef limestone at shallow depths. This geological formation is located about 10 m below the ground surface and has a V_s of 760 m/s. Therefore, the bottom of a borehole can be assumed as an engineering bedrock [21].

For the soil layers shown in Figure 2, the model proposed by Elgamal [10], called the pressure-dependent hyperbolic model, was adopted. This model is based on the framework of multiyield surface plasticity. This model also emphasizes the control of the accumulation of permanent shear strain in several sand types [10]. Elgamal [10] introduced the concept of incremental plasticity to simulate the nonlinearity of soil behavior. Therefore, this model is reliable in predicting soil behavior, especially during earthquake shaking. In addition, the incremental plasticity assumption is appropriate to analyze the permanent deformation, excess pore pressure, and hysteresis loop in soil dynamic problems, especially liquefaction. The list of model parameters is presented in Table 1. In Table 1, γ is the unit weight of soil, FC is the fines content, and c is the soil cohesion. Other soil properties, such as internal friction angle (ϕ), coefficient of soil permeability (k), corrected N-SPT or $(N_1)_{60}$, and coefficient of lateral earth pressure at rest (K_0), are also used. Elgamal [10] introduced reference effective confining pressure (p'_{reff}), peak shear strain (γ_{max}), liquefaction parameter (Liq), contractive behavior parameters (c_1 and c_2), and dilative behavior parameters (d_1 and d_2). These parameters were also adopted in the current work on the basis of the study of Elgamal [10].

Spectral acceleration based on nonlinear ground response analysis and empirical analysis was also studied. To investigate another effect of PGA on the soil layer, such as liquefaction, this study used the PGA obtained from the one-dimensional seismic ground response analysis in the assessment of liquefaction potential. The PGA applied in the conventional method for studying soil liquefaction is assumed linear for each depth. By contrast, the current study applied the nonlinearity of wave propagation using different PGA values at each depth. The conventional method proposed by Youd and Idriss [22] was employed to estimate liquefaction potential. The formulations to estimate liquefaction potential are expressed in the following equations:

$$CSR = 0.65 r_d \left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right)\left(\frac{a_{\max}}{g}\right), \qquad (1)$$

where r_d is the depth reduction factor; σ_v and σ_v' are the vertical and total effective stresses, respectively; g is the gravity acceleration; and a_{max} is the maximum PGA;

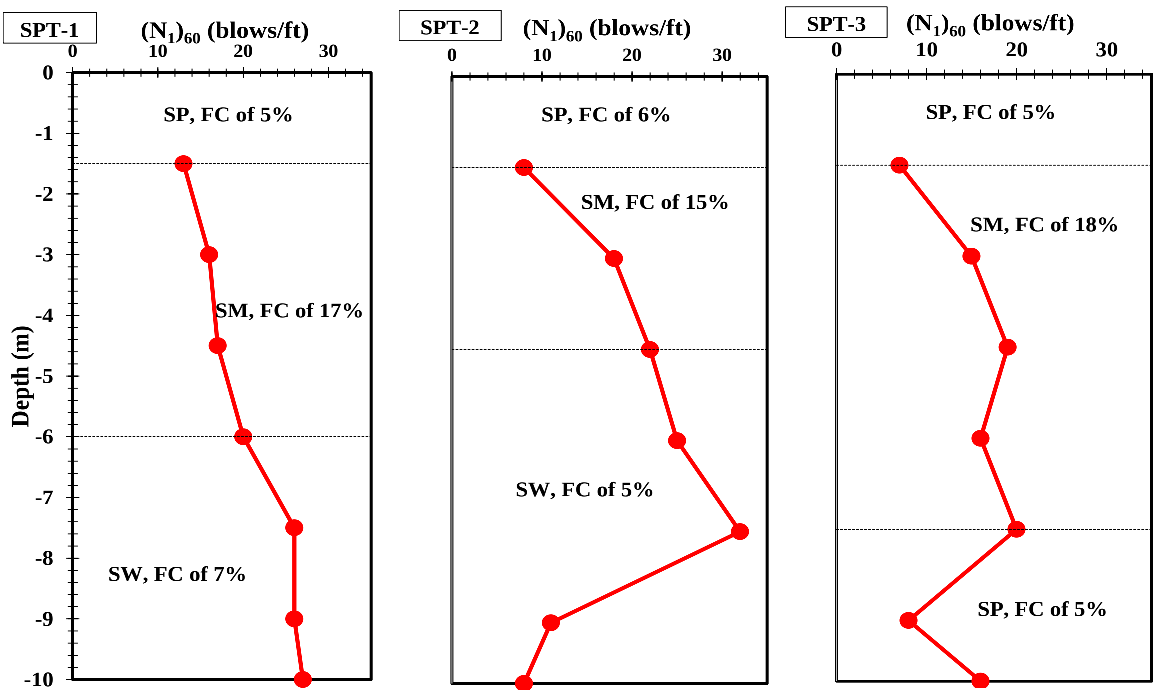

Figure 2. SPT and Soil Layer Interpretation (Redrawn and Modified from Mase [17]): (a) SPT-1, (b) SPT-2, (c) SPT-3

Tabel 1. List of Input Parameters used in the Nonlinear Ground Response Analysis

Site	Material	Thickness	γ	c	ϕ	FC	k	$(N_1)_{60}$	K_0	p'_{reff}	γ_{max}	Liq	c_1	c_2	d_1	d_2
		(m)	(kN/m^3)	(kPa)	(°)	%	(m/s)	blows/ft	(-)	(kPa)	(%)	(-)	(-)	(-)	(-)	(-)
SP-1	SP	1.5	17.1	0.3	28.3	5.0	1.1×10^{-7}	13.0	0.5	80.0	5.0	0.0	0.3	0.2	0.1	10.0
	SM	4.5	19.2	0.3	30.3	17.0	6.6×10^{-5}	16.0	0.5	80.0	5.0	0.0	0.1	0.5	0.5	10.0
	SW	4.0	20.5	0.3	31.5	7.0	6.6×10^{-5}	25.0	0.4	80.0	5.0	0.0	0.0	0.6	0.5	10.0
SP-2	SP	1.5	17.3	0.3	25.6	6.0	1.2×10^{-7}	8.0	0.5	80.0	5.0	0.0	0.3	0.2	0.1	10.0
	SM	3.0	19.4	0.3	33.3	15.0	6.3×10^{-5}	15.0	0.4	80.0	5.0	0.0	0.1	0.5	0.5	10.0
	SW	5.5	20.5	0.3	34.6	5.0	6.8×10^{-5}	22.0	0.4	80.0	5.0	0.0	0.0	0.6	0.5	10.0
SPT-3	SP	1.5	17.0	0.2	24.5	5.0	1.1×10^{-7}	6.0	0.5	80.0	5.0	0.0	0.3	0.2	0.1	10.0
	SM	6.0	18.7	0.3	31.4	18.0	6.1×10^{-5}	15.0	0.4	80.0	5.0	0.0	0.1	0.5	0.5	10.0
	SP	2.5	17.7	0.2	33.5	5.0	1.3×10^{-7}	15.0	0.4	80.0	5.0	0.0	0.3	0.6	0.5	10.0

Note

γ	: unit weight of soil	p'_{reff}	: effective confining pressure reference (based on [10])
c	: soil cohesion	γ_{max}	: peak shear strain (based on [10])
ϕ	: internal friction angle	Liq	: liquefaction parameter (based on [10])
FC	: fines content	c_1	: contractive parameter (based on [10])
k	: permeability index	c_2	: contractive parameter (based on [10])
$(N_1)_{60}$	: corrected SPT value	d_1	: dilative parameter (based on [10])
K_0	: coeficent of lateral earth pressure at rest	d_2	: dilative parameter (based on [10])

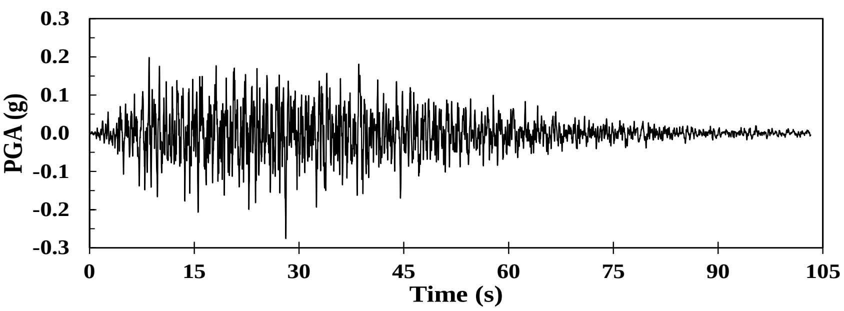

Figure 3. Synthetic Input Motion Used in This Study

$$CRR = MSF.\left(\begin{array}{l}\dfrac{1}{34-(N_1)_{60cs}}+\dfrac{(N_1)_{60cs}}{135}+\\ \dfrac{50}{\left[10(N_1)_{60cs}+45\right]^2}-\dfrac{1}{200}\end{array}\right), \quad (2)$$

where *CRR* is the cyclic resistance ratio, *MSF* is the magnitude scale factor (detailed information is available in the work of Youd and Idriss [22]), and $(N_1)_{60cs}$ is the corrected SPT added with FC correction.

The factor of safety of liquefaction (*FS*) is the main result of the analysis. Liquefaction can potentially occur if *FS* < 1. Otherwise, liquefaction is not likely. *FS* is expressed as follows:

$$FS = \frac{CRR}{CSR}. \quad (3)$$

The seismic ground response method and empirical analysis of liquefaction potential were combined in this work to investigate the liquefaction potential of the study area. The results can guide engineers in performing liquefaction analyses before construction.

3. Results and Discussion

Spectral Acceleration Reliability. The result is presented as spectral acceleration response (Figure 4). When a seismic wave is applied, spectral acceleration generally fluctuates according to the density and soil properties of the investigated locations. The fluctuation of the spectral acceleration response is affected not only by soil density and soil properties but also by soil thickness. High density soil (dense sand) tends to provide larger damping than low density soil (Figures 4a and 4b). The spectral acceleration response on each investigation point tends to decrease due to the composition of layers. In addition, the thickness of soil influences the spectral response of the soil itself. SPT-1 (Figure 4a) and SPT-2 (Figure 4b) present typical soil layers of dense sand with varying thicknesses. A thick soil layer with the same density tends to be more dampening the seismic wave than a thin soil layer. For SPT-3 (Figure 4c), the spectral acceleration response also fluctuates, especially for the transformation zone on each layer. As indicated in the figures, the thickness of the soil layer influences the spectral response of soil. For example, the thick medium sand layer reduces the wave propagating upward to the ground surface.

To inspect the reliability of SNI 03-1726-2012 [24], this study compared the spectral responses with those in the existing seismic design code curve. The comparison is presented in Figure 5. The SNI 03-1726-2012 [24] curve for Bengkulu City, especially the study areas, is generally reliable from the design aspect. However, the attention must shift should high-rise buildings be widely established in these areas [18]. The comparison shows that in long periods, the natural period of building (*T*) is exceeded by the spectral acceleration of the seismic ground response analysis. Hence, if intensive infrastructure development is initiated in the study area, then the design aspect should be carefully considered. In addition, a site investigation involving boring logs and SPT, V_s measurement, and CPT must be conducted to estimate soil resistance and site classification in the study area and thereby determine the suitable seismic design code. Bengkulu City is currently categorized as a developed city in Indonesia. Although high-rise buildings are still rare in Bengkulu City (where buildings have a maximum of four stories), the future development of building construction in this area is highly likely. Therefore, the government should carefully formulate and implement policies related to the administration of building construction in Bengkulu City because large earthquakes that could hit the city will certainly threaten the construction in the area [18].

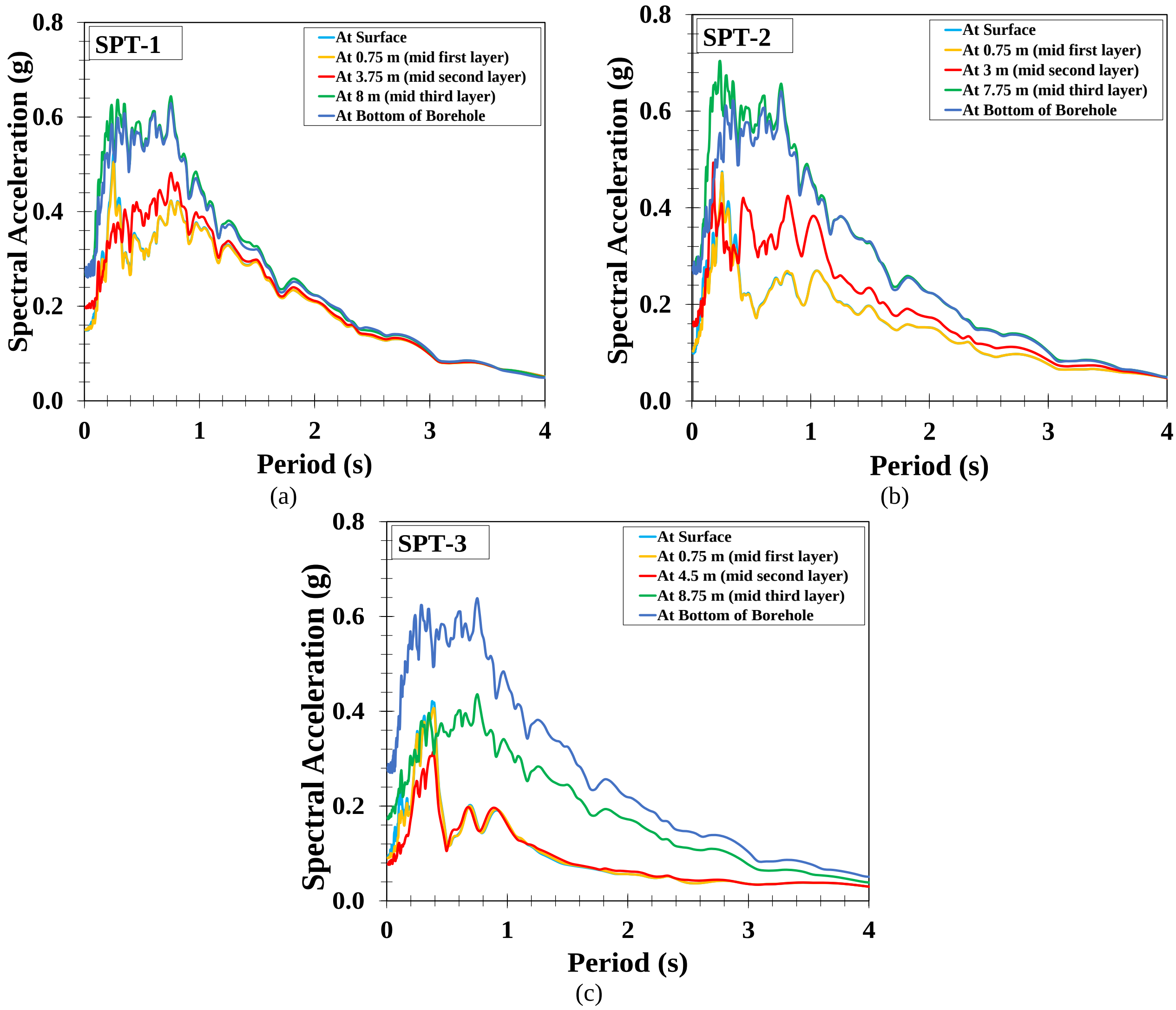

Figure 4. Spectral Acceleration due to Wave Propagation: (a) SPT-1, (b) SPT-2, and (c) SPT-3

PGA and Liquefaction Potential. The PGA of each depth was determined in this study using the nonlinear finite element simulation of wave propagation. The interpretation of the PGA at each depth is presented in Figure 6. The PGA of each SPT shows amplification and deamplification. The PGAs of SPT-1 and SPT-2 undergo amplification at mid-depth, whereas the PGA of SPT-3 experiences the reduction effect at mid-depth. Soil properties, soil thickness, and soil types are important in determining amplified or deamplified PGA. In this study, the resulting PGA for the ground surface is lower than the initial PGA (at the base).

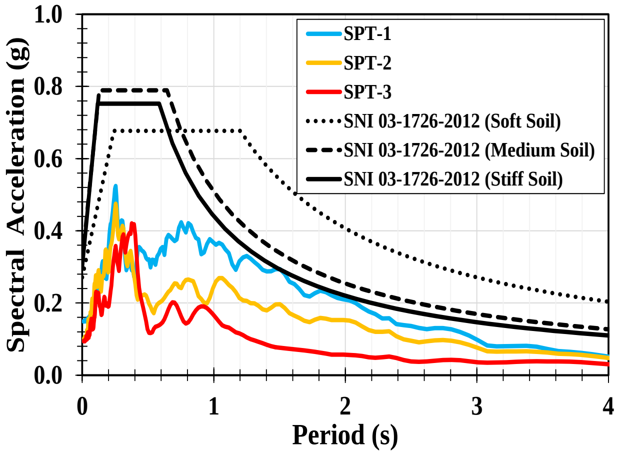

Figure 5. Spectral Acceleration Comparison

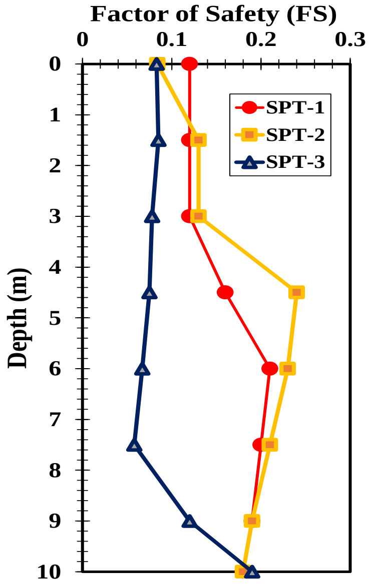

Figure 6. PGA of Each Layer

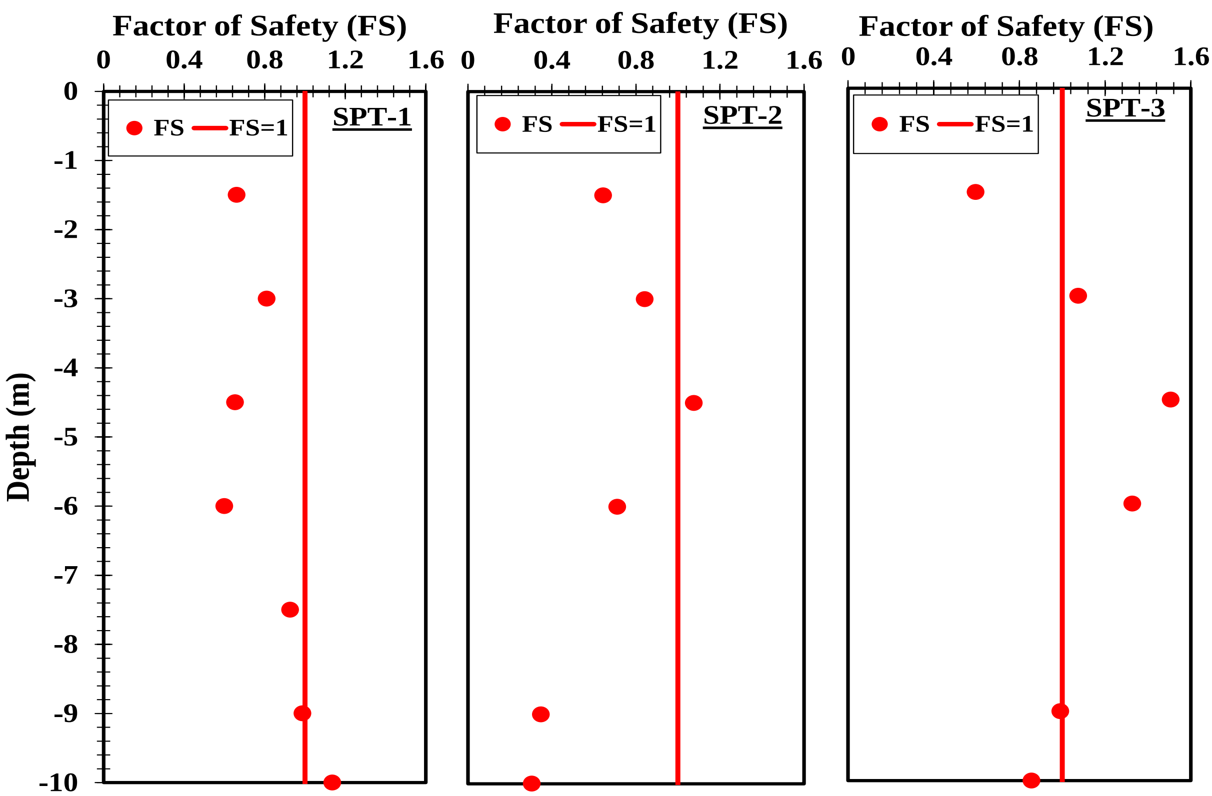

Figure 7. Liquefaction FS of Each Borehole: (a) SPT-1, (b) SPT-2, and (c) SPT-3

The result of the analysis of soil liquefaction is presented in Figure 7. No investigated point is categorized as totally safe. The unsafe zone of SPT-1 is found 10 m deep, whereas that of SPT-2 is found 4.5 m deep. The unsafe zone of SPT-3 is found 3–6 m deep. SPT-3 is clearly more vulnerable to liquefaction than the other SPTs even though the smallest PGAs were applied to SPT-3. This result indicates that in addition to PGA, soil resistance is the main factor that determines the vulnerability of liquefaction. This result confirms the findings of the studies conducted by Mase [17], Misliniyati *et al*. [25], and Monalisa [26], all of whom reported that liquefaction is likely at shallow depths along the coastal area of Bengkulu City. This result also verifies the likelihood of liquefaction occurring on loose and medium sandy soil along the coastal area. As liquefaction is possible at shallow depths of 0–9 m, building foundations must be carefully designed, especially for buildings with more than two stories.

4. Conclusion Remarks

This study aimed to investigate the seismic ground response along the coastal area of Bengkulu City after the earthquake on September 12, 2007. The nonlinear finite element method was applied. To inspect the liquefaction potential, this study applied nonlinear PGA to the conventional method. Spectral acceleration is influenced by soil type and soil thickness. The comparison of spectral responses shows that SNI 03-1726-2012 [24] is still reliable as the seismic design code for Bengkulu City. However, careful attention must be paid to medium and stiff soil, especially in the construction of buildings for $T > 1$ s. Although high-rise buildings are still rare in Bengkulu City, spectral responses should be carefully considered in the future.

The coastal area of Bengkulu City is vulnerable to liquefaction at shallow depths. Therefore, the design of building foundations should be carefully considered. The results of this work verify those of previous studies that suggested the possibility of liquefaction occurring at shallow depths along the coastal area of Bengkulu City. In addition, the results suggest that PGA and soil type are the main important factors in determining the liquefaction potential in the study area.

Acknowledgement

The author thanks BMKG for providing the data on the September 12, 2007 earthquake and the Soil Mechanics Lab, University of Bengkulu, for providing the site investigation data.

References

[1] Agency of Meteorology, Climatology, and Geophysics (BMKG), Earthquake Data in 2007, BMKG (in Indonesian), http://www.bmkg.go.id., 2016
[2] P.B. Schnabel, J. Lysmer, H.B. Seed, SHAKE: A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites", Report No. UCBIEERC-72/l2, Earthquake Engineering Research Centre, University of California, Berkeley, California, USA., 1972.
[3] K. Kanai, Relation between the Nature of Surface Layer and the Amplitude of Earthquake Motions, Bulletin Earthquake Research Institute, Tokyo, Japan, 1951.
[4] R.B. Matthiesen, C.M. Duke, D.J. Leeds, J.C. Fraser, Site Characteristics of Southern California Strong-Motion Earthquake Stations, Part Two, Report No. 64-15, Department of Engineering, University of California, Los Angeles, USA., 1964.
[5] J.M. Roesset, R.V. Whitman, Theoretical Background for Amplification Studies," Research Report No. R69-15, Soils Publications No. 231, Massachusetts Institute of Technology, Cambridge, USA., 1969.
[6] J. Lysmer, H.B. Seed, P.B. Schnabel, Bull. Seismol. Soc. Am. 61/6 (2012) 1213.
[7] I.M. Idriss, H.B., Seed, J. Soil Mech. Found. Div. ASCE 94/4 (1968) 1003.
[8] W.D.L, Finn, G.R. Martin, M.K. Lee, (1978), J. Geotech. Eng. ASCE.GTS/1 (1978) 472.
[9] Yoshida N, (1995), DYNEQ a computer program for DYNamic response analysis of level ground by EQuivalent linear method, version 3.25. http://www.civil.tohoku-gakuin.ac.jp/yoshida-j.html.
[10] A. Elgamal, Z. Yang, J. Lu. Cyclic1D: A Computer Program for Seismic Ground Response," Report No. SSRP-06/05, Department of Structural Engineering, University of California, San Diego, La Jolla, CA, USA. 2006.
[11] Z. Yang, J. Lu, A. Elgamal. J. Adv. Eng. Softw. 35/5 (2004) 249.
[12] H.B. Seed, I.M. Idriss, (1971) J. Soil Mech. Found. Div. ASCE 97/9 (1971) 1249.
[13] P.K. Robertson, C.E. Wride. J. Can. Geotech. 35/3 (1998) 442.
[14] R.D. Andrus, P. Piratheepan, S.B. Ellis, J. Zhang, and C.H. Juang. J. Soil Dyn. Eng. 24/9-10 (2003) 713.
[15] P. Monaco, S. Marchetti, Proceeding of the 4th International Conference on Geotechnical Engineering, Thessaloniki: Greece., 2007.
[16] L.Z. Mase. Teknosia 2/15 (2015) 25 (in Indonesian).
[17] L.Z. Mase (2018). J. Civil Eng. 25/1 53 (in Indonesian).
[18] L.Z. Mase. Int. J. Technol. 9/5 (2018) 910.
[19] SeismoArtif, Program for generating artificial Acceleration, Seismosoft Ltd. 2015) http://www.seismosoft.com.

[20] S. Gafoer, T.C. Amin, R. Pardede. Sheet of Geology Map for Bengkulu Sumatra, Indonesia. Geological Centre of Research and Development, Indonesia., 1992.
[21] R.D. Miller, J. Xia, C.B. Park, J. Ivanov, E. Williams. SEG Technical Program Expanded Abstracts Society of Exploration Geophysicists 1/1 (1999) 433.
[22] T.L. Youd, I.M. Idriss. J. Geotech. Geoenviron. Eng. ASCE 127/4 (2001) 297.
[23] Google Earth. Zonation of Bengkulu City. 2019. https://www.google.com/intl/id/earth/.
[24] SNI 03-1726-2012, Standard of Earthquake Resistance Design for Building, Ministry of Public Works, Jakarta, Indonesia, 2012, p.149 (in Indonesian).
[25] R. Misliniyati, Mawardi, Besperi, M.R. Razali, R. Muktadir. Inersia 5/2 (2014) 1 (in Indonesian).
[26] A. Monalisa, Undergraduate Final Project: Department of Civil Engineering, Faculty of Engineering, Universitas Bengkulu, Bengkulu, Indonesia, 2014.