Seismic hazard microzonation of ground response parameters in Bengkulu City, Indonesia

L Z Mase¹*, S Agustina¹, P W Anggraini¹

¹Department of Civil Engineering, Faculty of Engineering, University of Bengkulu, Bengkulu, 38371A, Indonesia,

*Corresponding author: lmase@unib.ac.id

Abstract. This paper presents the seismic hazard microzonation of ground motion parameters on the basis of earthquakes events in Bengkulu City. Geotechnical site investigation and geophysical survey were performed in Bengkulu City. Furthermore, data were used to observe the geological condition. The local seismic design code for soft soil was used to generate spectral acceleration, which was later used as the scaling factor to generate ground motion for earthquake simulation. One-dimensional seismic ground response analysis was conducted to simulate earthquake wave propagating through soil layers. Several parameters, such as peak ground acceleration (PGA), spectral accelerations (SA) at 0.2 s and 1 s, and seismic wave amplification factor were observed. Those parameters were also depicted in seismic microzonation maps and addressed to identify potential impact during the earthquake. The results showed that the possibility of structural building responses along coastal area of Bengkulu City is relatively high. Therefore, a local seismic design code is important to propose as the alternative for reliable seismic design code. In general, the results of this study could give a recommendation to local government to consider seismic resistance design for buildings in Bengkulu City.

Keywords: Seismic hazard, microzonation, earthquakes, ground response analysis.

1. Introduction

Bengkulu City is known as an area with high vulnerability to earthquake, in Indonesia. Several large earthquake events within last two decades had been occurred in this area. The first one is the 8.0 Mw Bengkulu-Enggano Earthquake and the second one is the 8.6 Mw Bengkulu-Mentawai Earthquake. Both earthquakes occurred in 2000 and 2007, respectively [1]. Mase [2] reported that during both earthquakes, the damage intensity in Bengkulu City was about VIII to IX in Modified Mercalli Intensity (MMI) Scale [3]. Regarding the seismotectonic activity in Bengkulu City, a study of seismic hazard assessment to the Bengkulu City sites are important.

The studies of earthquake impact in Bengkulu City had been performed by several researchers, such as Misliniyati et al [4], Mase [2], Mase [5], Farid and Hadi [6], Mase [1], and Misliniyati et al. [7]. Misliniyati et al [4] intensively studied the liquefaction impact during Bengkulu-Mentawai Earthquake in 2007 and found that Lempuing subdistrict was one of the most impacted areas. Mase [2] studied the characteristics of earthquakes in Bengkulu City within the period of 2000 to 2010 and concluded that within the return period of 2,475 years (2% probability of exceedance), maximum peak
ground acceleration (PGA\textsubscript{max}) in Bengkulu City could reach 1.8g. It indicates that Bengkulu City would be very vulnerable to undergo earthquake. Mase [2] also mentioned that there is a need to perform a further seismic hazard study in Bengkulu City. Mase [5] and Farid and Hadi [6] performed a numerical analysis and field measurement to investigate the soil sites in Bengkulu Province, especially in Bengkulu City. Both studies found that along coastal area of Bengkulu City is very vulnerable to undergo ground damage such as liquefaction, during past large earthquakes in 2000 and 2007. Mase [1] performed a study to examine the reliability of seismic design code [8] for Bengkulu City and concluded that the local design considering the detail information of soil sites should be composed for the seismic resistance design in Bengkulu City. Mase [1] also recommend that the development of seismic design code for low to medium stories buildings are important in Bengkulu City since those buildings’ types are dominant in Bengkulu City. Misliniyati et al [7] conducted a study of seismic hazard mitigation along coastal area of Bengkulu City and concluded that PGA > 1.0g are possible to occur in Bengkulu City. According to those previous studies, there is a concern to consider seismic resistance design in Bengkulu City. In general, previous studies had reached the conclusion that seismic hazard mitigation for engineering practice could be issue in Bengkulu City.

This paper presents a study of seismic hazard microzonation of ground response parameters in Bengkulu City, Indonesia. This study is initiated by collecting the site investigation data in Bengkulu City. The artificial ground motion from the study of Mase and Somantri [9] is used in seismic ground response analysis. Several ground motion parameters, such as PGA at ground surface, Spectral Acceleration (SA) at 0.2s, SA at 1s, and Amplification Factor are presented in this study. In addition, this study proposed the local seismic design code which concerns on soft soil site (SE) in Bengkulu City. The results of this study could lead a better understanding for the earthquake mitigation effort, especially in Bengkulu City.

![Figure 1. The layout of site investigation (modified from Google Earth [12])](image)

2. Study Area
The study area is presented in Figure 1. In Figure 1, total of 37 sites are investigated in this study. The site investigation method using cone penetration test (CPT) and geophysical measurement using microtremor measurement were performed to the sites. CPT is addressed to obtain the geological
condition of Bengkulu Site, whereas microtremor measurement is addressed to obtain the shear wave velocity profile of Bengkulu City sites. The typical geological condition in Bengkulu City based on site investigation is presented in Table 1. In general, the geological condition of Bengkulu Sites is dominated by sediments at 0 to 30 m depth [10]. Those sediments are composed by organic clay classified as OH and CH. Those sediments are found at depth of 0 to 1 m, with the unit weight (γ) of 17-18 kN/m³ and cone resistance (q_c) of about 2-10 kg/cm². The shear wave velocity (V_s) for this layer is about 90-270 m/s. At depth of 1-3 m, silty clay classified as CM is found. γ and V_s for this layer are about 17-18 kN/m³ and 160-350 m/s, respectively. q_c for this layer is about 10-30 kg/cm². At depth of 3-18 m, the materials composed by silty sand (SM), poorly graded sand (SP), and clayey sand (SG) are found. Those materials had γ of about 18-21 kN/m³ and V_s of about 200-500 m/s. q_c for this layer is about 30-80 kg/cm². The materials dominated by well graded sand (SW), clayey sand (SC), and clayey gravel is generally found at depth of 18-30 m depth. γ for this layer is about 19-22 kN/m³, whereas V_s is about 400-760 m/s. This layer has q_c of about 80-250 kg/cm². In general, ground water level of Bengkulu City is found at depth of 2 to 16 m depth. For depth of more than 30 m, rock layer is found. This layer has V_s more than 760 m/s and γ of about 22 kN/m³.

During the 8.6 Mw Bengkulu-Mentawai Earthquake in 2007, the sediments layers of Bengkulu Province Sites were very vulnerable to undergo ground damage called liquefaction [5]. Mase [5] also mentioned that liquefaction evidences were found in Bengkulu City, especially along coastal area of Bengkulu City. It indicates that the loose saturated sandy soils were extruded out due to the ground shaking. Hausler and Anderson [11] mentioned that massive structural damage and liquefaction were found during the 8.6 Mw Bengkulu-Mentawai Earthquake. Hausler and Anderson [11] also stated that the low-medium storeys buildings (i.e. 1 to 4 storeys buildings) were relatively more vulnerable to undergo earthquake damage in Bengkulu City during the earthquake.

| Layer | Depth (m) | Soil Type [13] | Unit Weight (γ) (kN/m³) | Resistance (q_c) (kg/cm²) | Shear Wave Velocity (V_s) (m/s) |
|-------|-----------|----------------|--------------------------|---------------------------|-------------------------------|
| 1     | 0-1       | OH/CH          | 17-18                    | 2-10                      | 90 m/s ≤ V_s ≤ 270 m/s       |
| 2     | 1-3       | CM             | 17-18                    | 10-30                     | 160 m/s ≤ V_s ≤ 350 m/s      |
| 3     | 3-18      | SM, SP, SC     | 18-21                    | 30-80                     | 200 m/s ≤ V_s ≤ 500 m/s      |
| 4     | 18-30     | SW, SC, GC     | 19-22                    | 80-250                    | 400 m/s ≤ V_s ≤ 760 m/s      |
| 5     | >40       | Rock           | >22                      | >250                      | V_s >760 m/s                 |

3. Methodology
The understanding of geological condition of Bengkulu City and the earthquake history in Bengkulu City is conducted before performing site investigation. Furthermore, this study is initially performed by performing the site investigation in Bengkulu City. Cone penetration test and microtremor measurement were performed to Bengkulu Sites. A further analysis to the site investigation data is also performed to obtain the specific geological condition in the study area. In addition, the earthquake characteristics based on the previous studies is also studied. In this study, an earthquake engineering study performed by Mase and Somantri [9] is considered, since that previous study had elaborated the seismic hazard analysis in Bengkulu City. Mase and Somantri [9] also proposed local seismic design code for soft soils in Bengkulu City, which can be addressed to quantify the possible earthquake damage in Bengkulu City.

After the site investigation data and earthquake history are performed, the non-linear one-dimensional seismic ground response analysis is performed to each investigated site. In this study, the pressure dependent hyperbolic model from Hashash et al. [14] is implemented to capture the cyclic behaviour of soils during the seismic wave propagation. Mase et al. [15] had presented the framework of non-linear seismic ground response analysis, as presented in Figure 2. The ground motion is applied at the engineering bedrock on each site. For this study, the engineering bedrock surface is assumed at 30 m depth. It is taken since V_s,0 found based on site investigation is generally found at 30 m depth.
Miller et al. [16], Mase et al. [15], and Adampira et al. [17] mentioned that \( V_s \) of about 760 m/s can be assumed as the indicator of engineering bedrock surface. Mase and Somantri [9] proposed the spectral acceleration design at bedrock for soft soils in Bengkulu City as presented in Figure 3. Therefore, the local spectral acceleration in this study is taken from Mase and Somantri [9]. From the proposed spectral acceleration, an artificial ground motion (presented in Figure 3) for soft soil site, which is generated based on the seismotectonic settings of Bengkulu City and seismic hazard assessment in Bengkulu City, is used.

During the seismic wave propagation, several ground motion parameters at ground surface, such as maximum peak ground acceleration (PGA\(_{max}\)), spectral acceleration (SA) at 0.2s, SA at 1s, and Amplification Factor, are observed. Those ground motion parameters are collected for each site and depicted into microzonation maps. The microzonation maps included the peak ground acceleration map, spectral acceleration map, and amplification map for Bengkulu City. The Inverse Distance Weighting (IDW) and Kriging interpolation methods are implemented to generate the microzonation maps for ground motion parameters during earthquake in Bengkulu City. In general, this study is expected to provide a better understanding of seismic hazard assessment in Bengkulu City. The results of this study could bring a recommendation for seismic resistance design in Bengkulu City.

4. Results and Discussion

4.1. Peak ground acceleration (PGA) and spectral acceleration (SA)

Maximum Peak ground acceleration (PGA\(_{max}\)) profile and spectral acceleration for each site are presented in Figure 4. PGA\(_{max}\) profile on each investigated site is presented in Figure 4a. Based on the results, it can be seen that the motion at engineering bedrock tends to amplify at ground surface. The input motions propagated through the soil layers. According to geological condition of Bengkulu City, the shear strength of soils on Bengkulu Sites increases with depth (Table 1). It indicates that the weaker layers exist at shallower depth. Yoshida [18] stated that during the seismic wave propagation, PGA\(_{max}\) on each layer is controlled by weak layer, such as soft clay and loose sand. Therefore, the PGA at ground surface at Bengkulu Sites tends to be larger than the input motion. Figure 4b presents the spectral acceleration obtained from non-linear seismic ground response analysis. From Figure 4b, it can be seen that spectral acceleration at ground surface due to the seismic propagation wave had
generally exceeded the existing seismic design code of Indonesia for soft soil or SE [8]. The major concerns are addressed to the spectral accelerations at short period, i.e. 0.2s and long period, i.e. 1s. For both spectral acceleration values, the spectral acceleration had exceeded the existing seismic design code of Indonesia. Considering the seismic ground response analysis results based on the representative ground motion from Mase and Somantri [9] study, it can be roughly estimated that there is a necessary to propose the local seismic design code that can cover a larger spectral responses in Bengkulu City.

**Figure 3.** Ground motion applied on each site investigation derived from Mase and Somantri [9] for soft soil site

**Figure 4.** Ground response on Bengkulu Sites due to seismic wave propagation (a) PGA\textsubscript{max} profile (b) Spectral Acceleration at ground surface
4.2. Microzonation map of PGA

The microzonation map of PGA based on non-linear seismic ground response analysis for Bengkulu City is presented in Figure 5. It can be seen that PGA_{max} at ground surface on each site ranges from 0.18g to 0.78g. Figure 5 also shows that PGA_{max} of 0.48g to 0.68g is dominant. In the western part or along coastal area of Bengkulu City, PGA_{max} values of 0.48g to 0.68g are generally found. Similar to western part, PGA_{max} values of 0.48g to 0.68g are also dominant on the eastern, northern, southern, and central parts of Bengkulu City. In general, the PGA_{max} value predicted in this study is consistent with several studies performed by Mase [1] and Misliniyati et al. [4]. Those mentioned that PGA values more than 0.3g could be found in Bengkulu City, especially along coastal area of Bengkulu City. In the central part of Bengkulu City, especially in Ratu Agung District, a small zone of PGA values ranging from 0.18g to 0.38g are found. The prediction is also consistent with Suhartini et al. [19] who mentioned that PGA values in Ratu Agung District ranging from 0.2g to 0.3g during the 8.6 Mw Bengkulu-Mentawai in 2007.

4.3. Microzonation map of SA at 0.2 s

Figure 6 presents the microzonation map of SA at 0.2s. According to International Code Council or ICC [20], SA 0.2s could be used to predict the ground response receiving by low storey buildings. The determination of low storey buildings is derived based on the relationship of \( T = 0.1 \) n, whereas \( n \) is the number of storeys. Therefore, period of 0.2s can be assumed as the low storey building, i.e. 1-2 storeys buildings. From Figure 6, it can be observed that SA at 0.2 s in Bengkulu City generally ranges from 0.8g to 1g. A small zone of SA at 0.2s with the value more than 1g is found in northern part of Bengkulu City, especially in Muara Bangkahulu District. During the 8.0 Mw Bengkulu-Enggano Earthquake in 2000, Farid and Hadi [6] mentioned that liquefaction and structural damage were found in this location. This area is also dominated by swamp deposit dominated by soft soil, such as soft clay and organic clay. Therefore, the larger ground response tends to happen in this area. Another small zone with the value of 0.3g to 0.8g is found in the central part of Bengkulu City, i.e. Ratu Agung District. In general, SA at 0.2s values for this area is relatively smaller than other areas in Bengkulu City. It indicates that a relatively smaller ground response is received by the low storey buildings in this area. However, several liquefaction impacts in Ratu Agung District were found during the 8.6 Mw Bengkulu Mentawai Earthquake in 2007 [11]. This is due to the fact that the relatively thin sediments and saturated sandy soils exist in this study area [10]. In general, the value of SA at 0.2s in Ratu Agung District is relatively consistent with Mase [1] study.

4.4. Microzonation map of SA at 1 s

Figure presents microzonation map of SA at 1s. As presented in Figure 7, it can be seen that in general, two zonation ranges are dominant in Bengkulu City. The first one is the zonation with SA at 0.2s ranging from 0.7g to 0.8g and the second one is the zonation with SA at 0.2s ranging from 0.8g to 0.9g. The first zonation can be found along coastal area of Bengkulu City, which is dominated by loose sandy soils. The second zonation are found in the eastern to northern parts of Bengkulu City. A zonation, which has range value more than 0.9 g are found along several swamp areas in eastern part of Bengkulu City and northern part of Bengkulu City. A zonation having range value of 0.3g to 0.7g is found in the central part of Bengkulu City. SA at 1s represents the response received by high storey buildings. Based on the results, it can be seen that along coastal area of Bengkulu City and several swamp areas in Bengkulu City tends to undergo a higher response during the earthquake shaking. For Ratu Agung District, Mase [1] had predicted that SA at 1s value ranged from 0.3 to 0.6g or in another word, the result of Mase [1] is consistent as predicted by this study.

4.5. Microzonation map of amplification factor

Figure 8 presents microzonation map of amplification factor. In general, investigated sites in Bengkulu City have the amplification factor of about 1.05 to 1.15, especially for the sites located along coastal area of Bengkulu City. Several areas (swamp areas) in western and northern parts of Bengkulu City
have amplification factor more than 1.15. The prediction of amplification factor along coastal area of Bengkulu City is generally consistent with Mase [1] study. Mase [1] mentioned that amplification factor in this area is relatively high. In Ratu Agung District, the maximum amplification factor is about 0.95. This could be caused by the existence of relatively thin sediment in this location which seems to be not much influencing ground motion amplification during the seismic wave propagation [1], [21].

Figure 5. Microzonation map of PGA

Figure 6. Microzonation map of SA at 0.2s
4.6. Proposed local spectral acceleration design for soft soil site in Bengkulu City

For engineering practice, the microzonation map could be transferred into a designed spectral acceleration. In this study, the local spectral acceleration design for seismic resistance building in
Bengkulu City is proposed. The design is composed based on the results of seismic hazard assessment performed in this study. It is addressed to cover the exceeding spectral acceleration during the seismic wave propagation at Bengkulu Sites. The comparison of local spectral acceleration design and the existing spectral acceleration, i.e. SNI 03-1726-2012 [8] for soft soil site (SE) is presented in Figure 9.

It can be seen that the proposed spectral acceleration design is more reliable in providing the relevant spectral acceleration design in Bengkulu City. It is because the average spectral acceleration resulted during the seismic ground response analysis is still below the proposed one. Therefore, for the practical purposes, the proposed spectral acceleration can be adopted in seismic resistance design, especially for soft soil sites in Bengkulu City.

![Figure 9](image_url)

**Figure 9.** Comparison of proposed local spectral acceleration and existing seismic design code for soft soil [8]

5. **Concluding Remarks**

This study performed a seismic hazard microzonation of Bengkulu City that is developed based on the local seismic condition investigated by previous study, i.e. Mase and Somantri [9]. A non-linear seismic ground response analysis is implemented to simulate the seismic wave propagation during the representative earthquake on soft soil site. The microzonation maps included the ground motion parameters such as PGA, SA at 0.2s, SA at 1s, and amplification factor are presented. A local spectral acceleration design for soft soil in Bengkulu City is proposed. PGA at ground surface is relatively high and consistent as predicted by several researchers such as Mase [1] and Suhartini et al. [19]. The amplification factor is relatively high for several areas in Bengkulu City, especially swamp area and coastal area. The results also concern on the possibility of structural building responses along coastal area of Bengkulu City since SA at 0.2s and SA at 1s are relatively high. The local seismic design code generated from this study could give a contribution to seismic resistance design for the buildings in Bengkulu City.

6. **Acknowledgement**

This research was supported by the Mandatory Research Fund Grant No. 3968/UN30.15/LT/2018, the competitive research fund in 2019 from the University of Bengkulu, and student creativity program of higher education (PKM-DIKTI) 2018. The authors would like to thank to Soil Mechanics Laboratory, and Geophysics Laboratory, University of Bengkulu, for site investigation performed in this study.
References

[1] Mase L Z 2018 Reliability Study of Spectral Acceleration Designs Against Earthquakes in Bengkulu City, Indonesia International Journal of Technology 9(5) pp 910-924
[2] Mase L Z 2015 Earthquake Characteristic in Bengkulu City Teknosa 2(15) pp 25-34 (in Indonesian)
[3] Wood H O, Neumann F 1931 Modified Mercalli Intensity of 1931 Bulletin of the Seismological Society of America 21(4) pp 277–283
[4] Misliniyati R, Mawardi M, Besperi, Razali M R, Muktadir R 2013 Liquefaction Potential Zonation in Lempuing Subdistrict, Bengkulu City Inersia 5(2) pp 69-75 (in Bahasa)
[5] Mase L Z 2017 Liquefaction Potential Analysis Along Coastal Area of Bengkulu Province due to the 2007 Mw 8.6 Bengkulu Earthquake Journal of Engineering and Technological Sciences 49(6) pp 721-736
[6] Farid M, Hadi A I 2018 Measurement of Shear Strain in Map Liquefaction Area for Earthquake Mitigation in Bengkulu City Telkomnika 16(4) pp 1597-1606
[7] Misliniyati R, Mase L Z, Syahbana A J, Soebowo E 2018 Seismic hazard mitigation for Bengkulu Coastal area based on site class analysis. In IOP Conference Series: Earth and Environmental Science 212(1) p. 012004
[8] SNI 03-1726-2012 2012 Standard of Earthquake Resistance Design for Building (Jakarta: National Standardization Agency) (in Bahasa)
[9] Mase L Z, Somantri A K 2016 Development of Spectral Response Design for Bengkulu City Based on Deterministic Approach Proc of the 20th Annual Meeting of Indonesian Society for Geotechnical Engineering (Jakarta: Indonesian Society of Geotechnical Engineering) pp 147–152
[10] Mase L Z, Sugianto N, Refrizon 2018 The Shear Wave Velocity Mapping for Seismic Hazard Mitigation in Bengkulu City, Competitive Research No. 2357/UN30.15/LT/2018 (Bengkulu: University of Bengkulu, Bengkulu, Indonesia)
[11] Hausler E, Anderson A 2007 Observation of the 12 and 13 September 2007 Earthquake, Sumatra, Indonesia. Build Change Report (Denver: Colorado, USA)
[12] Google earth 2019 Bengkulu City, Bengkulu Province, Indonesia (www.google.com)
[13] Howard A K 1984 The revised ASTM standard on the unified classification system Geotechnical Testing Journal 7(4) pp 216-222
[14] Hashash Y M A, Musgrove M I, Harmon J A, Groholski, D R, Phillips C A, Park D 2016 DEEPSOIL 6.1, user manual (Illinois at Urbana-Champaign: University of Illinois at Urbana-Champaign)
[15] Mase L Z, Tobita T and Likitlersuang S 2017 One-dimensional analysis of liquefaction potential: A case study in Chiang Rai Province, Northern Thailand, Earthquake Engineering Div JSCE, 73(4) pp. I_135-I_147
[16] Miller R D, Xia J, Park C B, Ivanov J and Williams E 1999 Using MASW to map bedrock in Olathe, Kansas Proc. SEG Technical Program Expanded Abstracts Society of Exploration Geophysicists pp 433
[17] Adampira M, Alielahi H, Panji M, Koohsari H 2015 Comparison of equivalent linear and nonlinear methods in seismic analysis of liquefiable site response due to near-fault incident waves: a case study Arabian Journal of Geosciences 8(5) pp 3103-3118.
[18] Yoshida N 2015 Seismic ground response analysis (London: Springer)
[19] Suhartini C E, Mase L Z, Farid M 2019 Microzonation of maximum peak ground acceleration due to the 12th September Earthquake in Ratu Agung District, Bengkulu City Proc Civil Engineering and Built Environment Conference 2019. Bengkulu, Indonesia, March 20.
[20] International Code Council 2009 International building code (USA: International Code Council)
[21] Refrizon, Hadi A I, Lestari K, Octari T 2013 Analysis of Peak Ground Acceleration and Seismic Vulnerability in Ratu Agung Bengkulu City Proc of Semirata FMIPA UNILA, Lampung, Indonesia; May 10-12 (in Bahasa)