Seismic hazard mitigation for Bengkulu Coastal area based on site class analysis

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Abstract. Bengkulu Coastal Area is a zone with high seismicity that has an acceleration of bedrock in the range 0.7-2.0g for the 2% probability of exceedance in 50 years. This area lies above the quarter sediment layers consisting of fluviatile, alluvium and coastal deposits which are very susceptible to undergo seismic hazards. Understanding about surface response spectra and free surface motion based on local site condition is very required in arranging Spatial Plan (RTRW) of Region. The objective of this study is to observe the response on ground surface of Bengkulu Coastal Area during the seismic loading. The site class analysis based on SNI-1726-2012 classification is performed to achieve this goal. The results obtained are surface response spectra and free surface motion, which are furthermore confirmed by the existing RTRW. In general, the conformity would suggest that disaster mitigation strategy should be actualized by the stakeholders.

1. Introduction

Bengkulu city is a capital city of Bengkulu Province, which is located at the western coastal area of Sumatra Island. This area has been known as the high seismicity area in Indonesia. There are two major earthquake sources located near the city. The first one is the subduction zone between Indo-Australia plate and Eurasia plate. The second one is the active fault crossing the Sumatra Island, which is locally known as Sumatra Fault or Semangko Fault [1]. As the results, the earthquakes frequently occur in this province. During last two decades, Bengkulu Province has experienced two strong earthquakes, i.e. on 4 June 2000 with a magnitude of 7.9 Mw and 12 September 2007 with a magnitude of 8.6 Mw. It is noted that the earthquake on September 2007 has resulted in the huge destruction and liquefaction along the coastal area of Bengkulu Province, including Bengku City [2].

Learning from the strong earthquake occurred in the past, the intensive study related to seismic hazard mitigation is performed. This study is presented to emphasize the influence of site class again response spectra on the surface and its advantages on planning building structure.

Several studies related to earthquakes and their followed catastrophic have been performed by several researchers [3]–[6]. These previous studies are focused on studying the earthquake characteristic in Bengkulu Province as well as the liquefaction phenomenon observed during the strong earthquakes in Bengkulu City, whereas the detail study related to the seismic hazard mitigation linked with the spatial plan of Bengkulu City (RTRW) has not performed yet. However, the basic understanding on earthquake impact in Bengkulu City has been achieved in those previous studies.
The objective of this study is to observe the response on ground surface of Bengkulu Coastal Area during the seismic loading. The site class analysis based on SNI-1726-2012 [7] classification is performed to achieve this goal. The results obtained from this study is surface response spectra and free surface motion, which are furthermore confirmed by the existing RTRW. In general, this study is expected to provide a deeper understanding of the seismic hazard mitigation in Bengkulu City. The results of this study would bring a recommendation to reconsider earthquake impact on the urban planning area in Bengkulu City.

2. Geological Condition and Earthquake Aspects in Bengkulu City
This work is focused on Bengkulu city (Figure 1) located at the strategic area on the western part of Sumatra coastal area. In the future, the infrastructure will significantly increase along with the increase in land use changes, which are used as spatial development in Bengkulu City. In terms of geological aspect, Bengkulu city lies in the arc-face basin of Bengkulu, which is a depressed area between Mentawai Islands in the western part and Sumatra Shelf in the eastern part. The basin of Bengkulu was formed due to the lump shifting, which occurred in earlier tertiary age [8]. The sedimentation process in the basin of Bengkulu was initiated in ologecne age and ended in plio-pleistocene age, which profiled the series of stratigraphy. The geological environment of Bengkulu basin consists of Seblat Formation, Lemau Formation, Simpang Aur Formation, and Bintunan Formation, as shown in Figure 2. In general, those formations are composed by sandstone, siltstone, claystone, and limestone. In addition, quarter sediment consisting of loose sand, gravel, silt, and clay materials.

The western coastal area of Sumatra and its surrounding areas are the region with the high seismicity level. This region is only 100 km from subduction zone in the west and Sumatra fault in the east, respectively. The subduction zone is the active tectonic zone between Indo-Australia and Eurasia plates, with the shifting velocity of 60-70 mm/year [1]. The earthquake aspect in Bengkulu City is controlled by the Sumatra Fault, i.e. Ketahun-Curup segment located in the east north of Bengkulu City. This segment is about 100 km in segment and has average shifting rate about 10 mm/year [1]. The activity of those tectonic region has been triggered so many earthquakes in Bengkulu City. Research Center for Geotechnology LIPI (Indonesian Institute of Science) recorded that the earthquakes occurred in 1770, 1861, 1883, 1906, 1931, 1958, 1979, 1991, 2000, and 2007 are
categorized as the significant earthquake in Bengkulu City. All earthquakes events are included in the seismic hazard analysis performed by Research Center for Geotechnology, LIPI [9].

As an area under the high seismicity area, there is a necessary to study the seismic hazard in Bengkulu City to provide the suggestion to the stake holder in considering the primary and secondary impacts of the earthquakes. In seismic hazard mitigation, the relevant ground motion, which can be used in the dynamic analysis either at bedrock or at surface should be known. This information is very important in related study such as liquefactions and other disasters following earthquakes [6]. Several studies focused on liquefaction phenomenon during earthquakes in Bengkulu City have been performed by many researchers [4]–[6], [9], [11], [12]. Basically, those studies used the site investigation data such as cone penetration test (CPT), standard penetration test (SPT), and shear wave velocity (Vs). Regarding the previous studies method, several locations representing the land use for the coastal area of Bengkulu City are selected (Table 1).

Those points listed in Table 1 are furthermore classified the site class. At those points, the bedrock motion and surface motion. The determination of site class is based on N-SPT values obtained from site investigation, whereas the shear wave velocity (Vs) is also determined by both the cone penetration test equipped by pore pressure sensor (CPTu) [13] and standard penetration test. The soil profile and Vs profile for the investigated sites are presented in Figure 4 and Figure 5, respectively. In Figure 4, the soil profile and N-SPT up to 30 m depth in DH-02 Kebun Tebeng are presented. Generally, the subsoils in Kebun Tebeng are dominated by sandy soils. The loose sandy soils are found from the ground surface up to 15 m depth, with the N-SPT average of about 8 blows/ft. the mixed sandy soils composed of quartz, clay, and weathered material are found on 15 m up to 30 m depth. These sandy soils have the N-SPT average of about 20 blows/ft.

Figure 2. The geology map of Bengkulu City [10].
Figure 3. Earthquakes occurred in Bengkulu City within radius of 500 km in 2017 [1].

| No | Land use      | Sites | Location     | Latitude (X°) | Longitude (X°) |
|----|---------------|-------|--------------|---------------|----------------|
| 1  | Farming Area  | DH-02 | Kebun Tebeng | 198533        | 9578975        |
| 2  | Housing Area  | CPTu-03 | Lempuing     | 197599        | 9577248        |
| 3  | Forestry Area | CPTu-05 | Teluk Sepang | 200266        | 9566293        |
| 4  | Plantation Area | CPTu-02 | Kel. Lingkar Barat | 199901       | 9575413        |

3. Probabilistic Seismic Hazard Analysis (PSHA)

Dynamic analysis used in this study is Probabilistic Seismic Hazard Analysis. The analysis is performed to the earthquakes occurred within radius of 500 km from the studied area (Figure 3), which in this case is Bengkulu City. Based on the database of Research Center for Geotechnology in Indonesia, the earthquakes triggered by the subduction zone and active tectonic region frequently occurred in Bengkulu area.

In Probabilistic Seismic Hazard Analysis (PSHA), several steps are performed. In this study, the EZFrisk [14] is used to perform PSHA. The analysis is initiated by obtaining the spectral acceleration at the bedrock. Afterwards, deaggregation analysis is performed to determine the spectral acceleration from the most credible earthquake. The spectral acceleration is furthermore matched by the period of PGA and compared to the results of hazard map by National Earthquake Center (PusGen) in 2017. The analysis to the site investigation data is the performed to determine the site class. The analysis is finished by the scaling spectral acceleration based on site class and the generating spectral acceleration.
Figure 4. Soil profile at DH-02.
Figure 5. The example of soil profile at CPTu-02, 03, and 05, respectively.
For example, the procedure of PSHA is implemented. In this study, PSHA Analysis considering the earthquake sources in Figure 7 is performed. The analysis is performed for the recurrence of 2,475 years with the exceedance probability of 2% in 50 years. These PSHA results of spectral acceleration at the bedrock are presented in Figure 7a. The deaggregation analysis at those locations is further performed. Based on the analysis results, the subduction earthquake is more dominant; therefore, Young (1997) attenuation model is used to generate the deaggregation spectral acceleration. Graph of deaggregation for the study area is presented in Figures 7b and 7c. After the deaggregation analysis, the spectral matching is performed. The matched spectral acceleration is then compared to the available database in EZFrisk results. The criteria to determine the suitable motion is the similarity in the shape of ground motion and the earthquake source mechanism. As presented in the previous section, the subduction mechanism can be categorised as the main earthquake source in the study area. Therefore, the ground motion due to the subduction is necessary in this study. Considering the criteria required to determine the ground motion at the bedrock, Chichi ground motion recorded at the bedrock is selected in this study. The ground motion of Chichi Earthquake is presented in Figure 7d. In Figure 7d, it can be seen that the maximum peak ground acceleration is about 1.1g. Generally, the peak ground acceleration obtained from the analysis is consistent with PusGen results, where in majority the maximum peak ground acceleration at the bedrock in the study area is about 0.7 to 2.0g.

The next step is to classify the site class. The site class for this study area is based on the timeaveraged shear wave velocity up to 30 m depth or $V_{S30}$ as shown in Figure 5. In general, the investigated sites are classified as Class E, with shear wave velocity of about 175 m/s. According to the amplification factor for PGA ($F_{PGA}$), the investigated sites have the amplification factor of 0.9g. The factor is furthermore multiplied by the matched spectral acceleration to determine the surface spectral acceleration at ground surface, as shown in Figure 8. The use of surface spectral acceleration is to obtain the natural period for the building, which is recommended for the study area.
Figure 7. The analysis of (a) spectral acceleration, (b) deaggregation graph, and (c) hazard curves, and (d) ground motion at bedrok for location 2.

The recommended natural period is associated with the resonance impact and earthquake frequency. In the figure, the recommended zone is indicated by x line. Based on the figure, the recommended natural period for building is about 1.6 sec. To obtain surface motion, the spectral acceleration is matched by the existing database. The surface motions for two locations are observed in Figure 9. Based on the surface motion in four areas, which represents the land use in the coastal area of Bengkulu city, it can be concluded that peak ground acceleration at the investigated locations are exceeding 1.0g. Spatial use released in 2010 indicated that those areas should be concerned is the housing area. Therefore, the seismic hazard mitigation should be implemented in the study area. The
earthquakes triggered by subduction zone is the main earthquakes type normally occurs in the coastal area of Bengkulu City. It is shown by deaggregation result and hazard curve due to various sources. Therefore, if the house areas are enlarged in the future, the motions implemented in the dynamic analysis of time histories are identical.

![Figure 8](image.png)

**Figure 8.** Spectral acceleration for (a) location 1 (b) location 2 (c) location 3 (d) location 4, with x as recommended structural period

![Figure 9](image.png)

**Figure 9.** Surface motion recapitulation for location 1-4, respectively.

4. **Concluding Remarks**

A PSHA Analysis of subduction and shallow crustal earthquake for the return period of 2,475 years and 5% damping in the coastal area of Bengkulu City is performed. Deaggregation results shows that the subduction earthquakes are more dominant in affecting the earthquake characteristic in Bengkulu City. The minimum peak ground acceleration of 1.0g could happen in the investigated. The results suggest that the minimum PGA of 1g could be considered in building design in Bengkulu City. The
PGA value also could reflect the subduction earthquake scenario, which is also addressed to minimize the structural damage during the earthquakes.

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