Seismic Response Analysis along the Coastal Area of Bengkulu during the September 2007 Earthquake

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Abstract

A strong earthquake of 8.4 M_w occurred at the Sumatra Subduction Zone in September 12, 2007. The area that underwent the impact of the earthquake was located along the coastal area of the Bengkulu Province. A seismic ground response study was then performed with reference to the event. Several site investigations, including standard penetration test and shear wave velocity tests, were conducted to understand the subsoil condition. The data were used to analyze a ground response during the earthquake. The amplification factor of each site was obtained, and a comparison of the spectral accelerations was performed. The results showed that the study area could undergo an amplification factor ranging from 1.1 to 1.5 during the seismic wave propagation. The spectral acceleration that resulted from the seismic response analysis was also within the design value. The study results could generally bring awareness to local engineers to consider the seismic design value for the coastal area of the Bengkulu Province, particularly if a stronger earthquake happens in the future.

1. Introduction

A strong earthquake of 8.4 M_w, which was triggered by the Sumatra Subduction Activity, occurred in the Bengkulu Province in September 12, 2007. The earthquake resulted in a huge damage in the Bengkulu Province. The damage along the coastal area was massive. Building collapses and soil damages (i.e., liquefaction, ground failure, and landslide) occurred [1]. With reference to the earthquake event, an intensive study on earthquakes was started in Bengkulu.

Several local researchers conducted earthquake studies in Bengkulu City. Mase [2] studied the damage intensity of the earthquake during the 8.4 M_w earthquake in the Bengkulu Province. According to that study, Bengkulu City, Northern Bengkulu Regency, and Muko-muko Regency were the most affected area during the earthquake, which had modified Mercalli intensity values of approximately IX to XI. Mase [3] also conducted a study on the earthquake characteristics in Bengkulu City. The result showed that an earthquake with a peak ground acceleration (PGA) of approximately
1.4 to 1.8g could happen in Bengkulu City, especially within the return period of 500 to 2500 years. Several researchers also conducted earthquake studies related to soil damage (i.e., liquefaction) in Bengkulu City. Misliniyati et al., [4] Monalisa, [5] Mase, and Somantri [5,6] investigated the vulnerability of liquefaction in the Bengkulu Province based on an empirical analysis (Seed and Idriss [8] and Idriss and Boulanger [9] Their studies focused on the coastal area of Bengkulu City that underwent liquefaction during September 2007. All previous studies reached the conclusion that the coastal area of the Bengkulu Province was vulnerable to undergoing liquefaction. The results confirmed the liquefaction evidence observed in the field during the earthquake. Previous studies generally focused on understanding the characteristics of earthquakes and investigating the vulnerability of soil damage during earthquakes. The seismic ground response caused by an earthquake, which is used to analyze the soil response, has not yet been investigated in these studies even if a rough interpretation of the earthquake impact was achieved.

This study presents an analysis of the seismic ground response during the 8.4 M<sub>W</sub> earthquake that occurred in September 2007 in Bengkulu. The PGA in the sites is analyzed. The PGA values obtained from the analysis are used to simulate a one-dimensional seismic ground response analysis of the sites. The amplification factor that resulted from the seismic analysis is also analyzed. In addition, the spectral acceleration at the ground surface obtained from the analysis is analyzed and compared with the designed spectral acceleration (i.e., SNI-1726-2002 [10] and SNI-1726-2012 [11]. This study is expected to provide a better understanding of the earthquake phenomenon in Bengkulu and bring awareness to the local engineers to consider the design value for the recurrence possibility of an earthquake in the future.

**Study area.** Figure 1 presents the layout of the study area. The sites are noted as BH-1 to BH-4, which are in Lais, Ketahun, Air Hitam, and Mukomuko, respectively. Lais and Air Muring are the areas, where the Northern Bengkulu Regency reigns, whereas Air Hitam and Mukomuko are under the Mukomuko Regency. All areas were reported as the most affected during the earthquake [1]. A standard penetration test (SPT) and a shear wave velocity (V<sub>S</sub>) measurement were performed in the study area. The earthquake epicenter in Figure 1 was located at the Indian Ocean. The earthquake was triggered by the activity of the Sumatra Subduction zone. However, the source of the earthquake existing in the Bengkulu Province was not only that zone, but also the Mentawai and Sumatra faults, which often produce earthquakes in Bengkulu and the surrounding provinces.

**Interpretation of the recorded ground motion.** No other seismic stations recorded the ground motion of the 2007 earthquake in Bengkulu, except for the Sikual Island Seismic Station (West Sumatra Province) (Figure 1). The station was very far from the earthquake epicenter (i.e., approximately 394 km). Figure 2 shows the ground motion recorded at the station and its spectral acceleration. The maximum recorded ground...
The Housner intensity of the ground motion was 13.45703 respectively. These maximum values were obtained at 61.16 s, 61.11 s, and 71.14 s, respectively. The PGV maximum (PGV\text{\text{max}}) and PGD maximum (PGD\text{\text{max}}) were 0.0408g, 4.19144 cm/s, and 10.2367 cm, respectively. The significant duration of the recorded ground motion (duration between 5% and 95% of the Arias Intensity) was 44.935 s.

**Site investigation results.** Figure 3 depicts the site investigation results. The subsoils of the study area are generally dominated by sandy soils. Loose sand (SP) layers existed on a shallow depth of 0 to 2 m with an (N\text{\text{t}})\text{\text{fo}} average of 1–5 blows/ft and a fine content (FC) of 5%. Silty sand (SM) layers were generally found in 2 to 27 m with an (N\text{\text{t}})\text{\text{fo}} average of 5 to 20 blows/ft and an FC of 12%. Clayey sand (SC) layers were found in 27 to 30 m deep with an (N\text{\text{t}})\text{\text{fo}} average of 20 to 30 blows/ft and an FC of 20%. The National Earthquake Hazard Reduction Program [13] categorized the study area as stiff soil (site class D) with a shear wave velocity average of up to 30 m (V\text{\text{s30}}) of 190–300 m/s.

**One-dimensional Non-linear Seismic Ground Response Analysis.** Two well-known models are used in the ground response field: equivalent linear and non-linear models (Figure 4). The equivalent linear model implements the equivalent assumption to approach the non-linear shear stress–shear strain. The shear modulus in this model is estimated by the equivalent assumption calculated by G_{eq}. However, the real condition of the shear stress and the shear strain is not equivalent linear. Therefore, the necessity to model the appropriate condition under dynamic or cyclic load transferred the idea to model soils, which behave as non-linear under cyclic loading. The non-linear model implements the non-linear shear strain–shear stress using G_{\text{\text{eq}}} based on the hyperbolic backbone curve.

Many non-linear soil models were developed to interpret the characteristic of the non-linearity of soils under dynamic or cyclic load. One of the models developed under the non-linear behavior of soil is the effective stress model proposed by Iai et al. [14] This model is composed of two important models. The first one is the multi-spring model with a hyperbolic non-linear defined in the strain space, which considers the rotation of the principal stress axis direction. This effect plays a role in the cyclic behavior of anisotropy consolidated materials, especially sands (Iai et al. in [14,15]) (Figure 5a). The multi-spring model is generated with the shearing section to a direction, in which the hyperbola model works. This model can also model the hysteresis loop. The second one is the effective stress model, which applies plastic shear work and stress (Figure 5b). This model simulates the excess pore water pressure as a function of the cumulative shear work for the liquefaction problem. Moreover, the effect of dilatancy is considered in the cyclic mobility behavior to the liquefaction front stated in the effective stress space. The model can also simulate a rapid or gradual increment in the cyclic strain amplitude under undrained cyclic loading.

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</table>

Figure 2. Ground Motion Recorded at the Sikuai Island Seismic Station Obtained from the Center of Earthquake Strong Motion Database [12]
Figure 3. Site Investigation Result

Figure 4. Estimation of The Shear Modulus in The Equivalent Linear Model and The Non-Linear Model
2. Methods

The site investigation was conducted along the coastal area of the Bengkulu Province. The site investigation included SPT and shear wave velocity measurement. The data obtained from the site investigation were collected and studied to understand the subsoil condition. No ground motion was recorded at the investigated locations (no seismic stations in the study area); hence, the ground motion recorded at the other locations was collected. The ground motion recorded at the Sikuai Island Station was collected from the Center of Earthquake Strong Motion Database. The ground motion was analyzed to observe the ground motion parameters. The attenuation model proposed by Youngs et al. [17] was used to estimate the PGA and the spectral acceleration at the sites (Figure 6). Furthermore, the spectral acceleration obtained from the attenuation analysis was used as the spectral acceleration target to generate the ground motion for the seismic response analysis. The spectral acceleration of the Sikuai Island ground motion was used to derive the spectral acceleration matched by the spectral acceleration of the sites (resulted from the attenuation model analysis). The spectral matching analysis was performed with the help of the SeismoArtif Program [18]. Figure 7 presents the generated ground motions used for the seismic response analysis. The generated ground motions were applied at the bottom of the investigated points (i.e., at a depth of 30 m) to perform the seismic ground response analysis using the effective stress model proposed by Iai et al. [11-12] At the bottom of each borehole, the layer was assumed as an elastic half space, where $V_S$ was assumed to be 500 m/s with a mass density of 2.2 t/m$^3$. This consideration was taken because no information on the depth of the seismic and engineering bedrocks were available. The amplification factor during the seismic wave propagation was defined as the comparison between the acceleration at the ground surface and the input acceleration. The spectral acceleration caused by the seismic wave propagation on each layer of each site was analyzed and compared to the designed spectral
acceleration. The designed spectral accelerations considering 10% probability of exceedance in 50 years (SNI-1726-2002 [10]) and 2% probability of exceedance in 50 years (SNI-1726-2012 [11]) were compared herein with the resulted spectral acceleration.

3. Results and Discussion

Amplification factor: Figure 8 presents the comparison of the accelerations at the ground surface that resulted from the seismic response analysis and the input motion. The input motion on each site applied at the bottom general tended to amplify at the ground surface. The PGA at the ground surface was compared with the input motion applied to estimate the amplification factor on each site. Figure 9 illustrates the interpretation of the amplification factor on each site.

The amplification factor on the study area that generally ranged from 1.1 to 1.5. BH-1 (Lais) had the highest amplification factor. The smallest one was BH-3 (Air Hitam). The study area was dominated by sandy soils with a low soil resistance and a depth up to 16–21 m. These soil layers were classified as SP and SM (silty sand) and had an \( N_{10} \) average of 1–16 blows/ft. These soil layers were not compact and tended to behave as weak layers. The low soil resistance also reflected the small shear strength of these layers. Therefore, during the wave propagation, the input motion amplified at the...
ground surface because the weak layers tended to undergo a longer shaking than the hard layers. Moreover, the weak layers provided a lower damping to reduce the earthquake energy. This result was consistent with that of Yoshida [19] who noted that the PGA at the ground surface was controlled by the shear strength of the weakest layer. Therefore, in the study area, the weak layer existing at a shallow depth tended to control the PGA at the ground surface, which tended to amplify the input motion to up to 1.5 times. The result of the amplification factor analysis could be a suggestion for the local engineers to consider the amplified acceleration at the ground surface in the design.

**Spectral acceleration.** In 2002, the Indonesian design code of SNI-1726-2002 was released to guide engineers...
in designing the earthquake load for structures. The code considered 10% probability of exceedance in 50 years for the building design. The seismic activity in Indonesia intensively increased during the last decade. Many mega-earthquakes occurred within the past 20 years (i.e., Bengkulu Earthquake in 2000, Aceh earthquake in 2004, Nias earthquake in 2005, Bengkulu–Mentawai Earthquake in 2007, and Padang Earthquake in 2009). These earthquakes provided lessons to the government to revise the old seismic design code. In 2012, SNI-1726-2007 was released as the successor of SNI-1726-2002. This code considered 2% probability of exceedance in 50 years for the building design. The spectral acceleration obtained from the seismic response analysis was compared herein with both codes (Figure 10). The spectral accelerations on each layer were still within the design values of both codes. The spectral acceleration of the layers reached the maximum value at a period of 0.2 to 0.5 s with a spectrum value of 0.1 to 0.6g. However, massive building collapses were found in the field. In contrast, the spectral acceleration of the earthquake at the ground surface still did not exceed the design values, which seemed to indicate that house buildings and other structural buildings, which collapsed because of the earthquake shaking, had not considered the design code. Considering this result, this study would like to bring awareness to the people living in the study area to follow the seismic design code in the construction steps to avoid the same or a greater destructive impact in buildings if a stronger earthquake occurs in the future.

4. Conclusions and Recommendation

This study focused on the seismic response analysis in the coastal area of the Bengkulu Province during the 8.4 Mw strong earthquake that occurred in September 12, 2007. The concluding remarks are as follows: 1) The sites underwent site amplification during the wave propagation. The sites were inclined to amplify from 1.1 to 1.5 times. BH-1 had the highest amplification factor, whereas BH-2 had the lowest amplification factor in the study area. The existence of SP and SM layers with low soil resistance and shear strength at a shallow depth controlled the acceleration at the ground surface during the wave propagation. 2) The spectral accelerations that resulted from the seismic ground response analysis were generally within the design value of the spectral acceleration for the 2% and 10% probabilities of exceedance in 50 years. This comparison brings awareness to local engineers to consider the designed spectral acceleration to avoid damage as huge as that during the 2007 earthquake, especially if a stronger earthquake occurs in the study area in the future. 3) The study area was generally dominated by sandy soils; hence, the analysis of the liquefaction potential can be performed in the future.

Acknowledgment

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References


