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SEISMIC RESPONSE IN MUARA BANGKAHULU SUB-DISTRICT, BENGKULU CITY USING THE CONCEPT OF WAVE PROPAGATION

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P-ISSN: 2301-8437
E-ISSN: 2623-1085

ARTICLE HISTORY
Accepted:
5 Juni 2024
Revision:
20 September 2024
Published:
30 September 2024

ARTICLE DOI:
10.21009/jpensil.v13i3.45746

Abstract

The position of Bengkulu Province, which is flanked by the subduction zone between the Euro-Asian and Indian-Australian plates to the west, and the Sumatra Fault zone to the east, makes Bengkulu City one of the areas prone to earthquake disasters. Muara Bangkahulu District is one of the sub-districts in Bengkulu City. Muara Bangkahulu sub-district is an area that functions as a government centre, trade and service centre, and one of the education centres in Bengkulu City. This study aims to determine the ground response in the Muara Bangkahulu sub-district area during an earthquake. The wave propagation method used in this study is a one-dimensional equivalent of linear and nonlinear modelling that propagates earthquake waves from bedrock to surface. The results of this study are Peak Ground Acceleration (PGA), amplification factor, earthquake acceleration time history, and acceleration spectra response. The results of this analysis will be compared between equivalent linear and nonlinear values. The results of this study can also help us realise and further consider the value of seismic design in the Muara Bangkahulu sub-district area, mainly if a stronger earthquake occurs in the future.

Keywords: Earthquake, Peak Ground Acceleration, Time History of Earthquake Acceleration, Amplification Factor, Acceleration Spectra Response

Introduction

Bengkulu City, a coastal area facing the Indian Ocean, is highly susceptible to earthquake disasters (Pribadi et al., 2016). The frequency and magnitude of past earthquakes, such as the 2000 earthquake with a magnitude of 7.9 Mw and the 2007 earthquake of 8.6 Mw, underscore the urgency and importance of our research in this area (Mase, 2018; Sugianto & Farid, 2017).

Figure 1 describes the area of Bengkulu Province, which the Sumatra Fault, Mentawai Fault, and Sumatra Subduction Zone flank. The activity of the Sumatra Subduction Zone, Mentawai Fault, and Sumatra Fault can trigger earthquakes in Bengkulu Province and its surrounding areas (Haridhi et al., 2023; Puteri et al., 2019). Therefore, Bengkulu Province is one of Indonesia's regions that is prone to earthquake disasters.

Muara Bangkahulu sub-district is one of the sub-districts in Bengkulu City. Muara Bangkahulu sub-district is an area that functions as a central government area, central trade and service area, public service area, education area and security defence area (Farid & Mase, 2020).The government centre area includes the Bengkulu City government office. The trade and service centre area includes markets and shophouses in the Muara Bangkahulu sub-district. The public service facilities area includes the sub-district office and Muara Bangkahulu Police Station. Education areas include schools and universities. The security defence area includes the Bengkulu Class II B Women's Correctional Facility.

Figure 2 shows the location of the study area. The recorded point locations from MB-1 to MB-6 each represent several urban villages in the Muara Bangkahulu sub-district, Bengkulu City. Previous research focused on understanding earthquake characteristics and investigating the vulnerability of ground damage during earthquakes. This research focuses on seismic design response comparing equivalent linear and nonlinear data at each point of the study site. Microtremor and shear wave (V_S) measurements were conducted at each study site.

Figure 1. Seismotectonic Conditions in Bengkulu Province (modified from Mase, 2018)

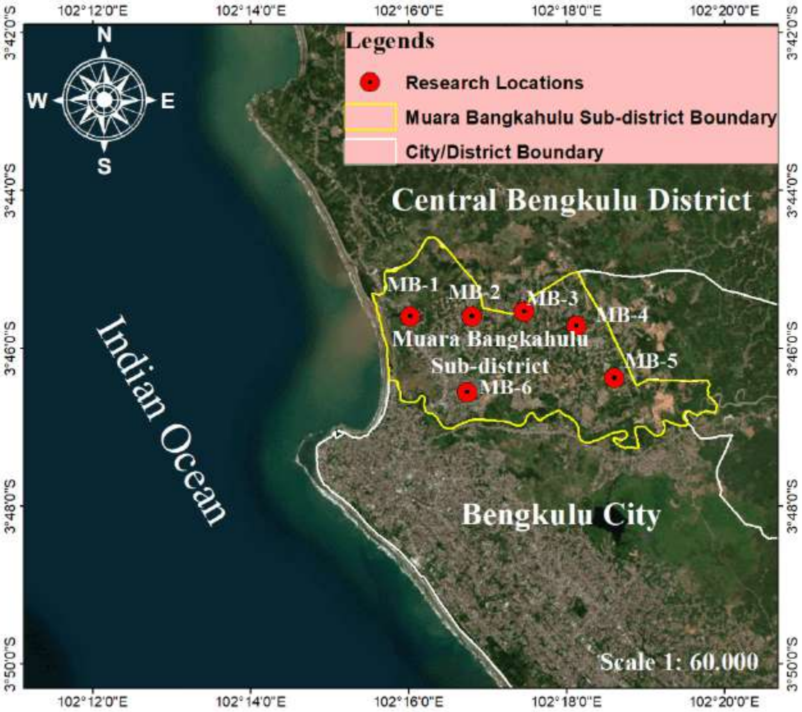


Figure 2. Research Locations

Seismic response analysis is the one-dimensional propagation of seismic waves through horizontal soil layers (Adampira et al.,2015; Mase & Likitlersuang, 2021). This one-dimensional seismic response analysis is used to solve the problem of vertical wave propagation through horizontal layered soil deposits (Chang et al., 2014; Hashash & Park, 2001). Misliniyati et al. (2019), mentioned several influencing factors in calculating ground motion. The influencing factors include soil characteristics, response to ground vibrations, and seismic waves (Pehlivan et al., 2016; Zaalishvili, 2016).

In field response, equivalent linear model and nonlinear model are usually used. Using linear assumptions, the equivalent linear model approximates nonlinear shear stresses and shear strains (Assimaki & Kausel, 2002; Kaklamanos et al., 2015). Qodri et al. (2021) mentioned that seismic response analysis begins with propagating seismic waves in bedrock to the ground surface. Mase (2018) mentioned that a one-dimensional seismic response analysis was conducted to see the soil response from wave propagation to earthquake shaking. The results obtained from this seismic response analysis are PGA and ground response spectra acceleration (Bozorgnia et al., 2016; Kale et al., 2015). In recent years, researchers have applied one-dimensional wave propagation methods using equivalent linear and nonlinear methods (Misliniyati et al., 2019).

Peak Ground Acceleration (PGA) is the maximum ground acceleration value due to earthquake vibrations in an area within a certain period (Massinai et al., 2016; Razin et al., 2021). The PGA value indicates the earthquake risk level in the area, the higher PGA value, the higher danger and risk of earthquakes (Kossobokov & Nekrasova, 2018; Parvez et al., 2017). The PGA value determines the earthquake risk level with a PGA value of 0.3g-0.4g, including a high risk, and a PGA value > 0.4g, including a very high risk (Fathani et al., 2008).

Accelerated Response Spectra are used to analyse structures (Arros & Doumbalski, 2013). The spectral response can describe the natural period of a building structure simply by estimating the building level (Perrone et al., 2020; Wang et al., 2021). The SA value is put into graphical form to determine the spectral acceleration and determine the maximum value at a certain period (Salsabil et al., 2018).

The amplification factor is a significant difference in wave magnification between layers (Huang et al., 2021). Amplification occurs due to the difference in velocity in shear wave motion (V_S) between bedrock and soil layers (Huang et al., 2021). The higher the value of the amplification factor, the greater the ground motion acceleration on the surface (Kumar & Baro, 2015; Partono et al., 2013).

This research was conducted at six points in Muara Bangkahulu District. This research discusses seismic response analysis that produces Peak Ground Acceleration (PGA), amplification factor, earthquake acceleration time history, and acceleration spectra response. The ground acceleration spectra are compared with the designed acceleration spectra response from the National Standardization Agency in SNI 1726:2019 (2019). This study compares the results of the equivalent linear and nonlinear methods on soil data in the Muara Bangkahulu District.

Research Methodology

One-dimensional Wave Propagation

This study uses Pressure Dependent Hyperbolic (PDH) modeling for nonlinear comparisons. The data used for this modelling are primary and secondary. The primary data used is the soil layer obtained from the research location, and the secondary data used is the scaled 2007 Bengkulu-Mentawai earthquake wave data (Mase, 2017) as motion input. The stages in the nonlinear and linear equivalent one-dimensional seismic wave modelling of the PDH model use the 1D equivalent linear and nonlinear response analysis program. Meanwhile, the analysis of the equivalent linear method can be seen in Figure 3. The shear modulus (G_{max}) in the soil has a value that is not constant depending on the structural characteristics of the layer. However, in the analysis of seismic parameters using the equivalent linear method, the shear modulus (G_{max}) value is considered constant and has the highest value. Thus, the resulting seismic parameters will tend to increase.

The linear equivalent method uses a transfer function to determine the phase of each frequency during vibration and the amplification factor. This function also depends on the soil layer components (shear wave velocity, specific gravity, and layer thickness) to determine the frequency of the input waves that can be amplified or de-amplified. The transfer function helps convert input waves in the form of time histories of earthquake accelerations from bedrock in the time domain into the frequency domain using the Fast Fourier Transform (FFT) algorithm. The output waves in the frequency domain are converted back into the time domain (time history) using the inverse FFT algorithm.

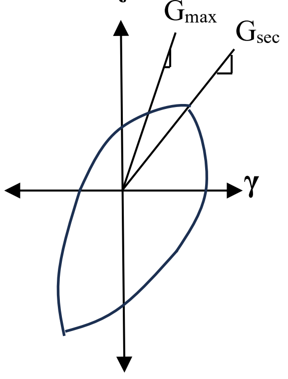


Figure 3. Shear Modulus of Equivalent Linear Model (modified from Yoshida, 2015)

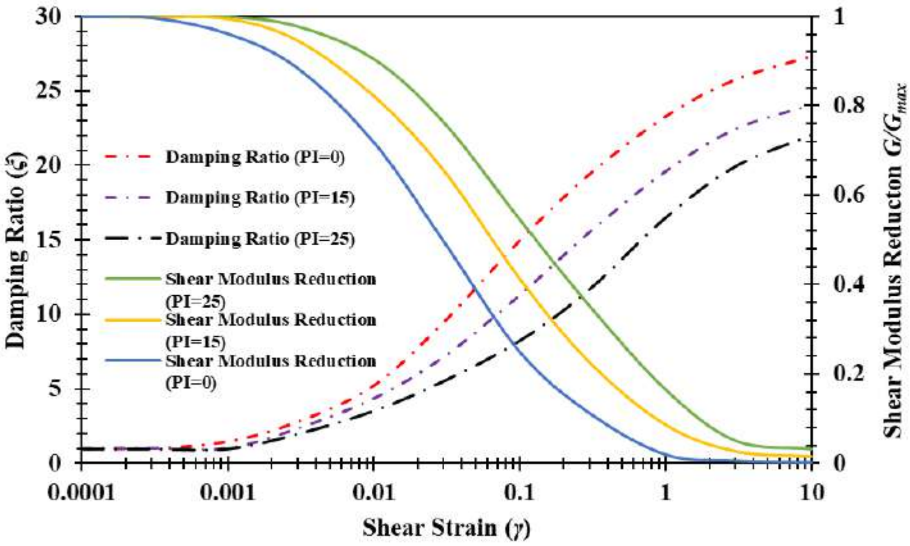


Figure 4. G/G$_{max}$ curve and damping ratio for clays (modified from Mase, 2017 and Vucetic & Dobri, 1991)

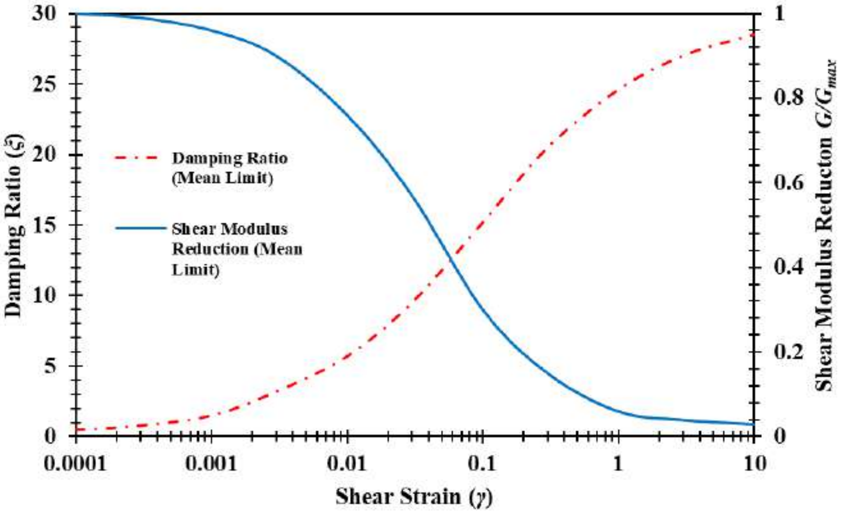
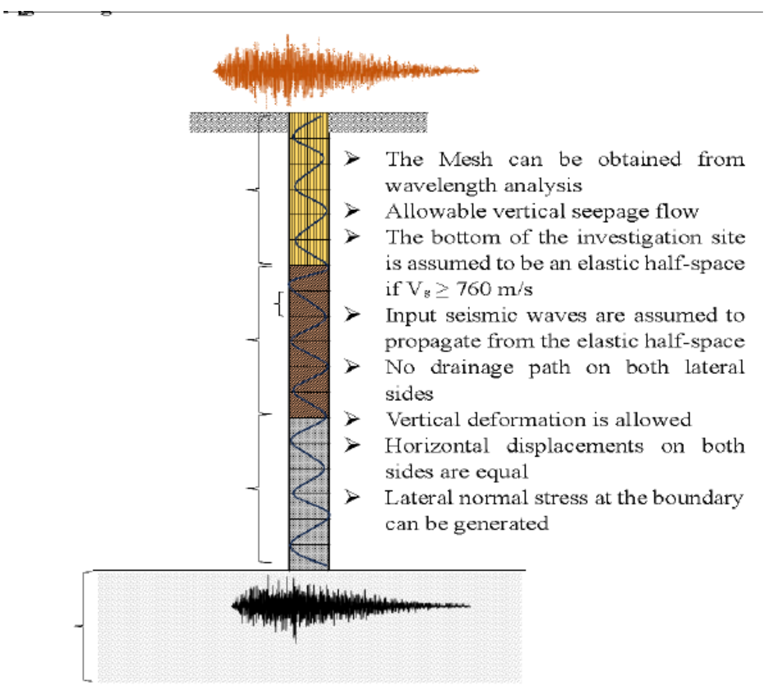


Figure 5. G/G$_{max}$ curve and damping ratio for sandy soil (modified from Mase, 2017 and Seed & Idriss, 1991)

The steps in this PDH modelling. First, analyse the soil profile that has been made by inputting all soil layer data such as soil type, soil thickness of each layer (h), soil volume weight (γ_{sat}), and shear wave velocity (V_S). Second, input the dynamic parameters and PI values. This study determines the dynamic parameters such as shear modulus ratio (G/Gmax) and damping ratio (ξ); it is determined based on the soil type by using reference curves. For granular soils, the G/G_{max} curve of Seed and Idris (1991) is used, while for cohesive soils, the G/G_{max} curve of Vucetic and Dobri (1991) is shown in Figure 4 and Figure 5. Third, input bedrock parameters in the form of soil volume weight (γ_{sat}), damping ratio (ξ) and shear wave velocity (V_S). Figure 6 shows that the wave propagation scheme uses the wavelength analysis method, in which earthquake waves are propagated from the bedrock to the ground surface. It was fourth, selecting the scaled 2007 Bengkulu-Mentawai earthquake wave motion input.



- The Mesh can be obtained from wavelength analysis
- Allowable vertical seepage flow
- The bottom of the investigation site is assumed to be an elastic half-space if $V_s \geq 760$ m/s
- Input seismic waves are assumed to propagate from the elastic half-space
- No drainage path on both lateral sides
- Vertical deformation is allowed
- Horizontal displacements on both sides are equal
- Lateral normal stress at the boundary can be generated

Figure 6. 1D Wave Propagation Scheme

Define the minor strain damping by selecting a frequency independent of the dumping matrix type. The final results of this data analysis are then processed again to produce Peak Ground Acceleration (PGA) parameters, amplification factors, and acceleration response spectra. These parameters are needed to compare the equivalent linear and nonlinear models. After that, the results of this seismic response analysis are processed again in the form of graphs.

Research Data

Earthquake Wave

In 2007, Bengkulu City experienced a strong earthquake with a magnitude of 8.6 Mw that caused maximum damage. This earthquake wave data is called the scaled 2007 Bengkulu-Mentawai earthquake wave developed by Mase (2017). The magnitude of the PGA value of 0.33g can be seen in Figure 7. This earthquake wave data will be used as input motion to analyse one-dimensional equivalent linear and nonlinear earthquake wave propagation using the Pressure Dependent Hyperbolic (PDH) model.

Soil Layers

Figure 8 is the result of the research site investigation. Field investigation in Muara Bangkahulu sub-district: This research used microtremor measurements. Each sample represents several sub-districts in this sub-district. The soil layer in the research area is generally dominated by sandy soil. The clay layer is found at shallow depths of 0 to 10 m at several points in the research location. The sand layer is found at a depth of 0 to 25 m. SNI 1726:2019 (2019) and The National Earthquake Hazard Reduction Program (NEHRP), categorises the study area at Points MB-1, MB-2, MB-3, and MB-5 as hard soil (site class SC) with a shear wave velocity to a depth of 30 m (V_{s30}), which is 360-760 m/s. Points MB-4 and MB-6 are categorised as medium soils (site class SD) with shear wave velocities to a depth of 30 m (V_{s30}), 180-360 m/s.

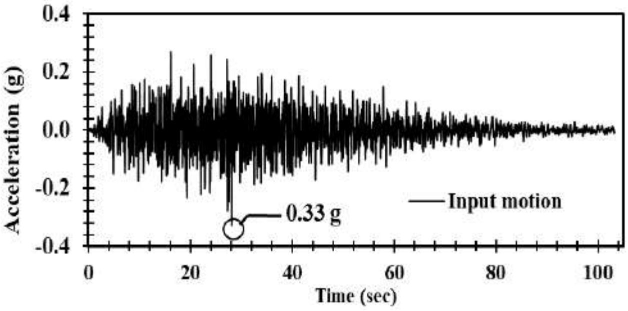
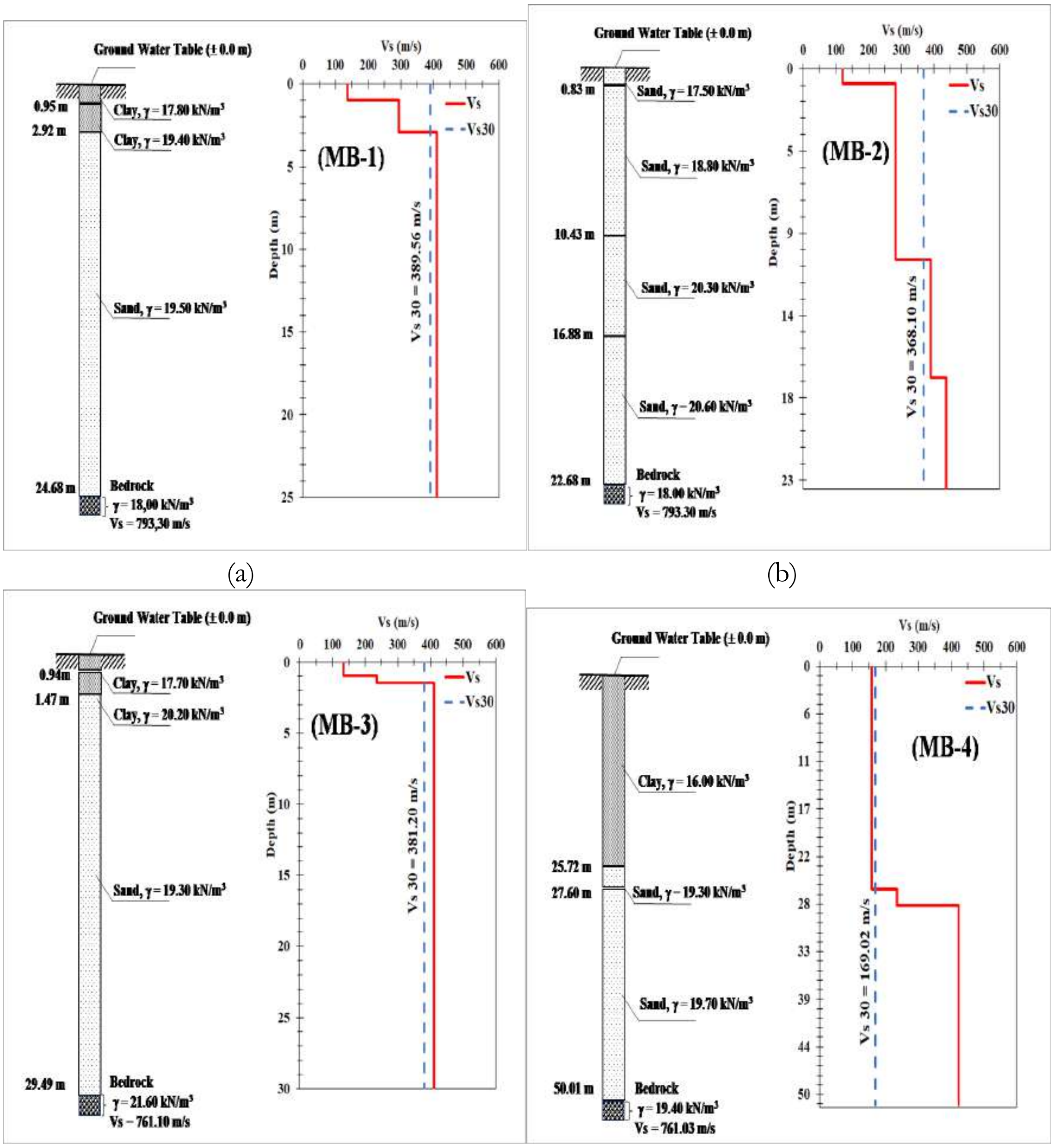


Figure 7. Scaled Input Wave (Mase, 2017)

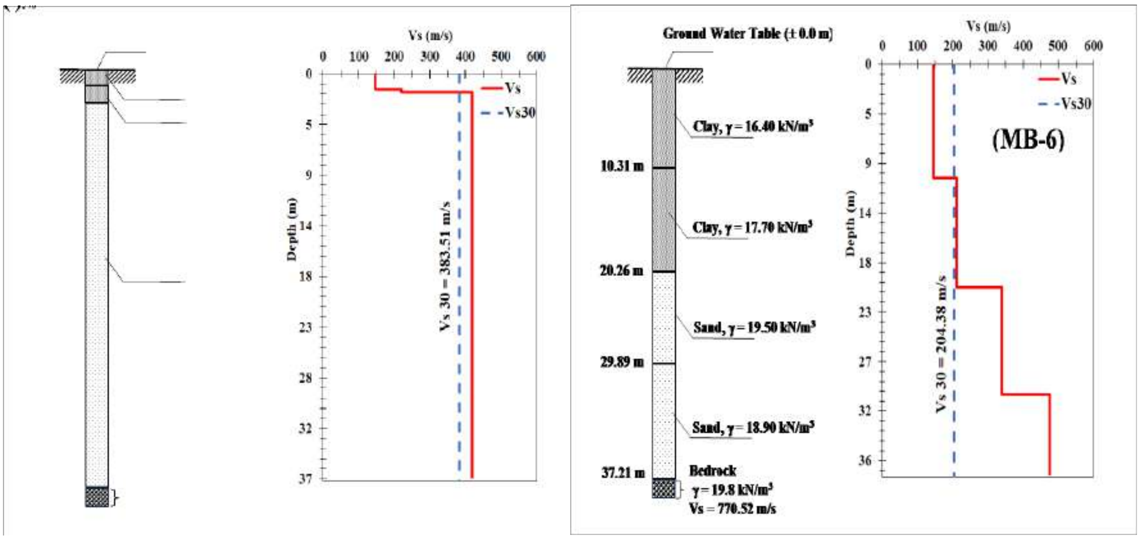


(a)

(b)

(c)

(d)



(e) (f)

Figure 8. Soil Layer Data of the Research Site at Points (a) MB-1, (b) MB-2, (c) MB-3, (d) MB-4, (e) MB-5, and (f) MB-6.

Research Results and Discussion

Amplification Factor

Comparison of the PGA from the surface and input motion results in an amplification factor value. The amplification factor gives an idea of the change in earthquake acceleration from the bedrock to the surface. This study uses a site class that refers to the Vs_{30} value calculated based on the Vs profile at the research point. Furthermore, from Vs_{30}, the site class that refers to the sni along with the amplification factor is determined. The site class of the soil at the research location can be seen in the soil layer subchapter.

The amplification factor can be affected by the value of Vs_{30}. The larger the value of Vs_{30}, the smaller the amplification value and the larger Vs_{30}, the smaller the amplification value. An example occurs at point MB-6 which experiences the largest amplification factor. Meanwhile, point MB-4 experienced a deamplification of 0.87 in the non-linear method and 0.96 in the equivalent linear method. In addition to Vs_{30}, many things can affect the value of the amplification factor. Geological structure, soil layer density, depth of bedrock and the epicenter of the earthquake. Geological structure can affect the magnitude of amplification by knowing whether the research point is close to a fault or not. Soil density is related to stiffness. The denser the soil layer, the smaller the amplification factor value. The softer the soil layer, the greater the amplification factor value. The duration of wave propagation is greater when it occurs in a soft layer, thus increasing the amplification factor value. The depth of the bedrock can determine the amplification factor value. The deeper the bedrock, the smaller the amplification factor value (Bustari & Wibowo, 2023). Figure 9 shows the graph of the amplification factor value at each point of the studied area. The magnitude of an amplification factor will affect how fast the ground motion acceleration is on the surface (Partono et al., 2013).

The higher the value of the amplification factor, the greater the potential for structural damage due to earthquakes. Amplified soils tend to amplify the intensity of earthquake vibrations, which can cause more severe damage to the infrastructure that stands on them. Figure 9 shows that the nonlinear amplification factor has a range of 0.87-1.22, while the equivalent linear amplification factor has a range of 0.96-1.53. Referring to the research of (Partono et al., 2013), the value of the equivalent linear amplification factor is greater than the nonlinear one, so it has a high potential for structural damage to buildings in earthquakes.

Peak Ground Acceleration (PGA)

In this research, the maximum acceleration of each layer of results in seismic response analysis in graphical form can be seen in Figure 10. At point MB-1 to point MB-6, the highest PGA value is shown in the surface layer; the highest surface layer value is found in the equivalent linear value than the nonlinear surface value. The lowest PGA is located in the bottom layer; the lowest bottom layer value is found in the linear equivalent of the nonlinear value.

The PGA value determines the earthquake risk level, with the PGA value 0.3g-0.4g included in the high risk and the PGA value> 0.4g in the very high risk (Fathani et al., 2008). Referring to the research of Fathani et al. (2008), the nonlinear PGA value is in the range of 0.29g-0.40g, so it is included in the high risk. The equivalent linear PGA value is 0.32g-0.50g, included in the very high risk. The research of Mase et al. (2020) concluded that linear equivalents can increase the PGA value and show a high overestimation. The method magnifies the shear stress that occurs after shear strain so that it becomes perfectly plastic (Yoshida, 2015). This is shown at Point MB-6, which has a greater thickness of clay than the linear equivalent.

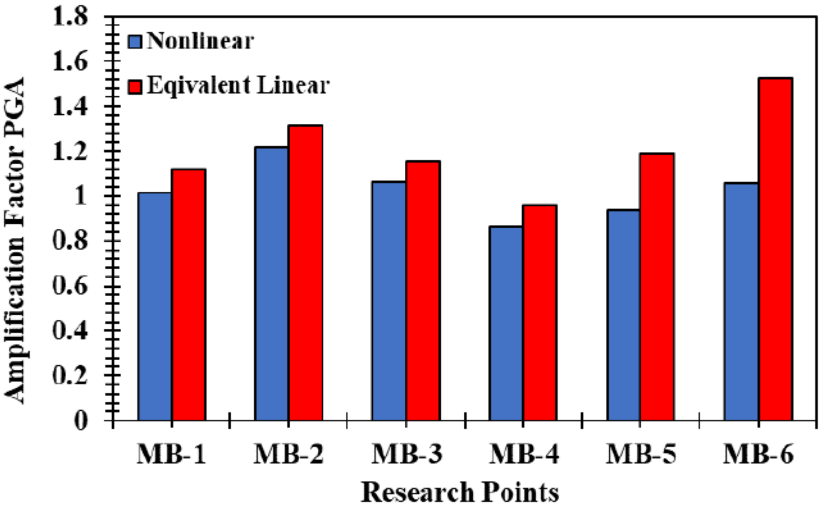
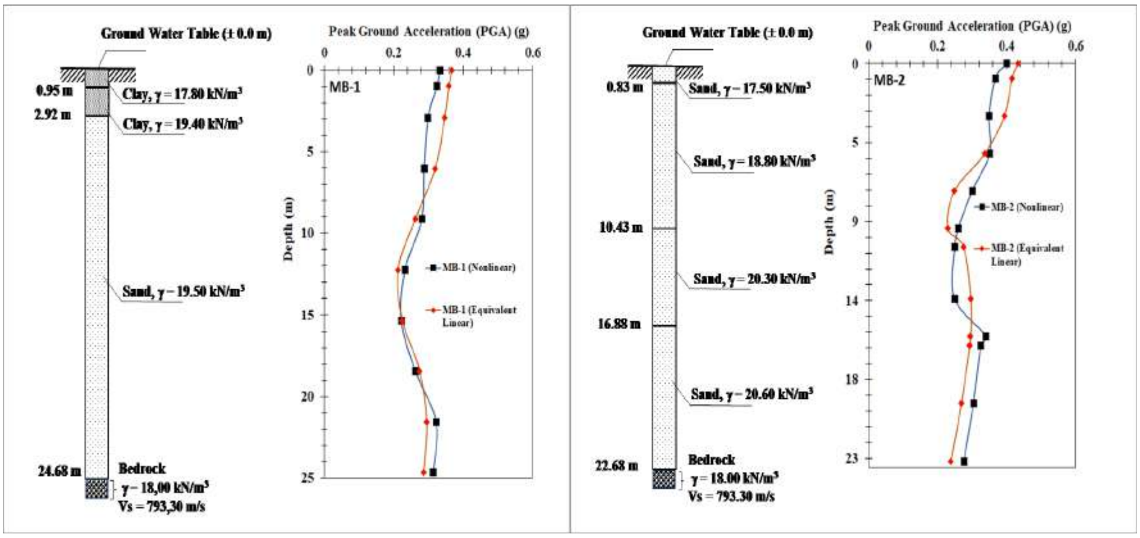
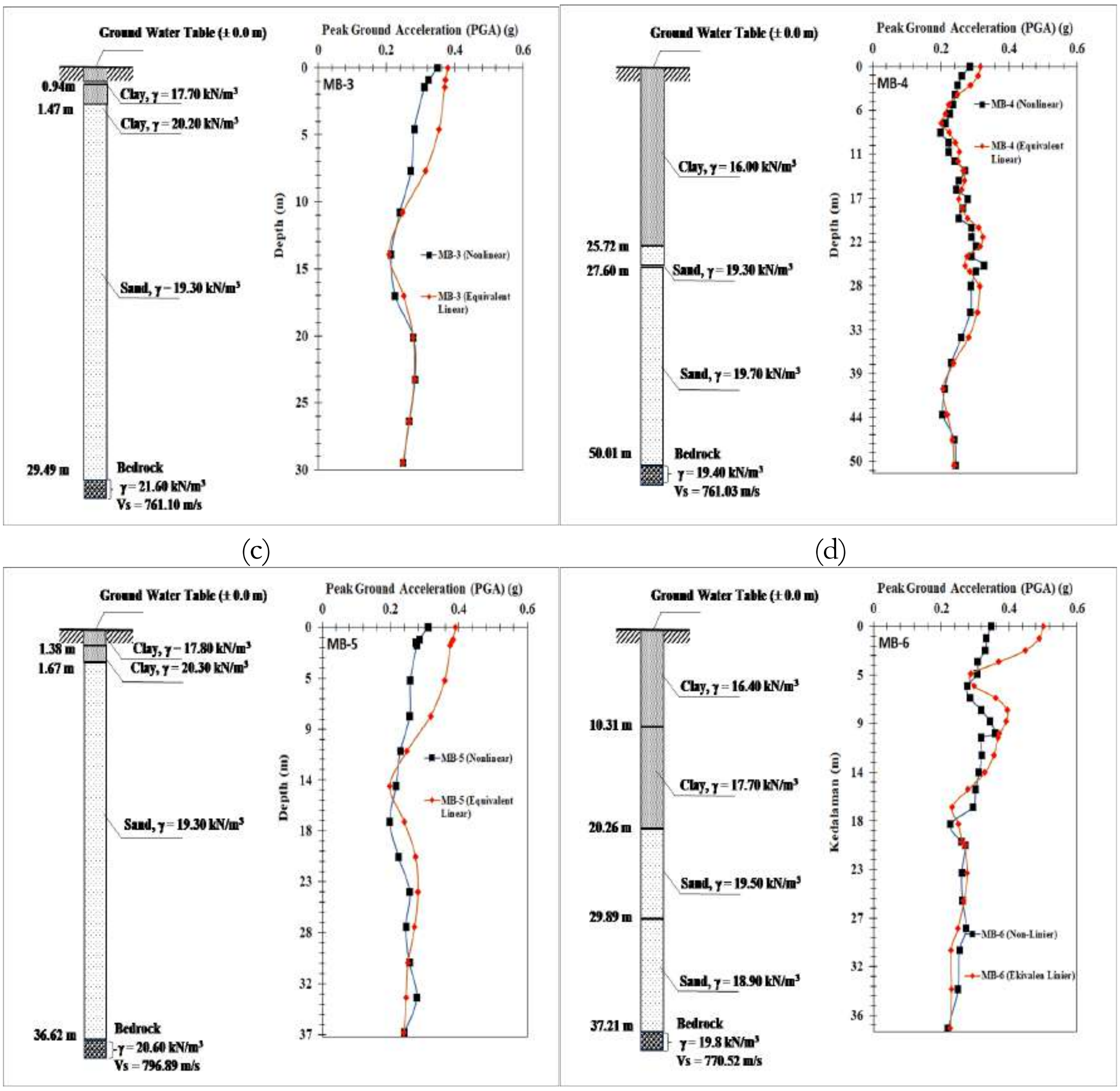


Figure 9. Amplification Factor Analysis Results



(a) (b)



(c) (d)

(e) (f)

Figure 10. Peak Ground Acceleration (PGA) Analysis Results (a) MB-1, (b) MB-2, (c) MB-3, (d) MB-4, (e) MB-5, and (f) MB-6.

Time History of Earthquake Acceleration

The results of this study can be seen in the acceleration of earthquake waves in the form of a graph in Figure 11. The input motion at each location applied at the bottom generally tends to strengthen at the ground surface. The research results show that the most significant acceleration occurs in the equivalent linear method and the lowest acceleration in the motion input. The earthquake wave acceleration value of the nonlinear method is in the range of 0.29g-0.40g, and for the equivalent linear method is in the range of 0.32g-0.50g. The most considerable equivalent linear method earthquake wave acceleration value is at Point MB-6 at 0.50g and the lowest at Point MB-4 at 0.32g. The most considerable nonlinear method earthquake wave acceleration value was at Point MB-2 by 0.40g, and the lowest at Point MB-4 by 0.29g.

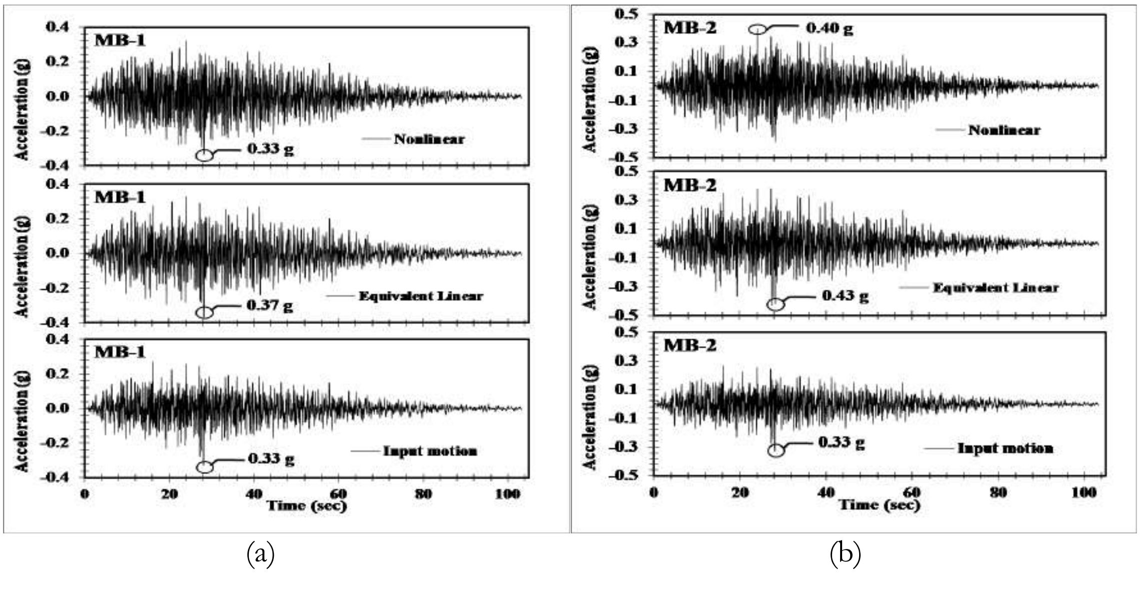
The wave propagation results based on the equivalent linear approach tend to produce more significant maximum acceleration than the nonlinear approach. According to Finn et al. (1978), this is due to the overestimation of shear stress, which also causes the PGA value to be more significant. In addition, the influence of soft layers with relatively low resistance characteristics causes the magnification of earthquake wave acceleration near the surface. Similar results were also reported by Adampira et al. (2015) and Yunita et al. (2015) for case studies of soil layers in Iran and Turkey.

Acceleration Spectra Response

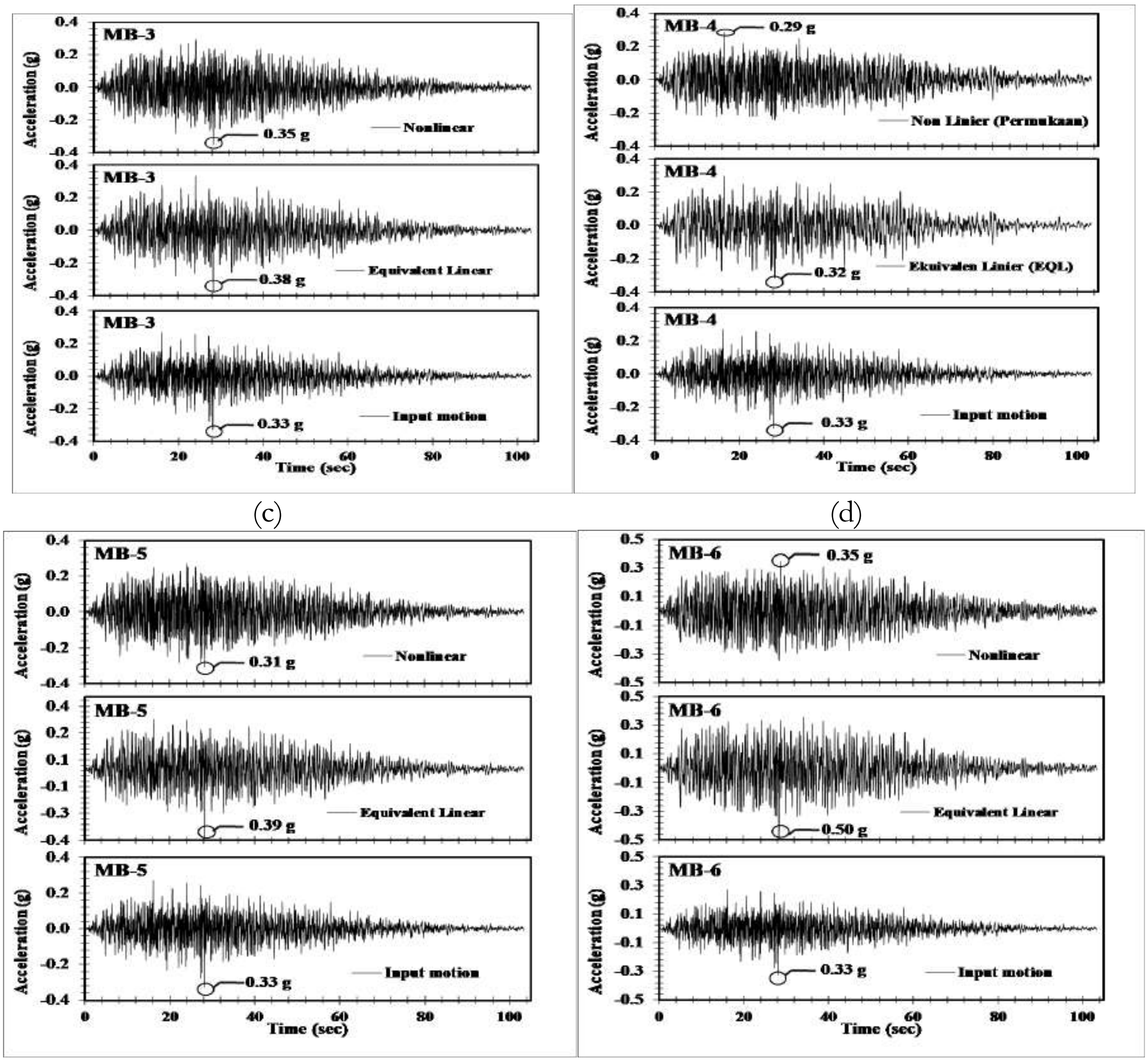
Figure 12 shows the acceleration spectra from this study with different values for each period. The analysis shows that the spectral acceleration of the input wave increases slowly until it reaches a peak at a period of 0.2 seconds. The equivalent linear and nonlinear acceleration values show an increase in spectral acceleration compared to the input wave. According to the International Code Council or ICC (2006), the period or Tn of the building can be estimated with the Tn approach of 0.1n (where n is the number of floors of the building). So, Tn of 0.2 seconds helps predict the ground response received by low-floor buildings in resonant periods on floors 1-2, while Tn of 1 second represents the ground response received in high-floor buildings (SNI 1726:2019, (2019).

Figure 12 compares the spectral acceleration values of the seismic response analysis results and the design acceleration spectra of SNI 1726:2019. The results show that from Point MB-1 to MB-6, based on the design of SNI 1726: 2019, tends to be greater than the equivalent linear and nonlinear spectral acceleration values at short periods in soft and medium soils, so at that point, there is a need for a review of low-rise buildings. Points MB-2, MB-5, and MB-6 show that the equivalent linear and nonlinear spectral acceleration values exceed the design limits of SNI 1726:2019 in soft, medium, and hard soil. So, at Points MB-2, MB-5, and MB-6, there is a need to review medium-story buildings, educational areas, and shops.

Sand layers dominate the research site. This occurs at Points MB-2, MB-3, and MB-5, which have sand layers up to a depth of 36.62 m, and clay layers tend to be thin, namely 1.47 m. The results show that the three research locations experience wave magnification due to earthquake damping. Sand soils have characteristics that are not dense and have a larger pore volume than clay soils so that they can dampen earthquake waves. The results show that these three research locations experienced wave magnification due to the small damping of earthquake waves. Figure 12 shows that MB-2, MB-3 and MB-5 experienced wave acceleration magnification at a short period (0.2 s), so a review of low-rise building structures is necessary. Point MB-4 shows that the equivalent linear and nonlinear spectral acceleration values exceed the design limits of SNI 1726: 2019 at long periods, so there is a need for a review of high-rise buildings, and the area is the central government area of Bengkulu City.



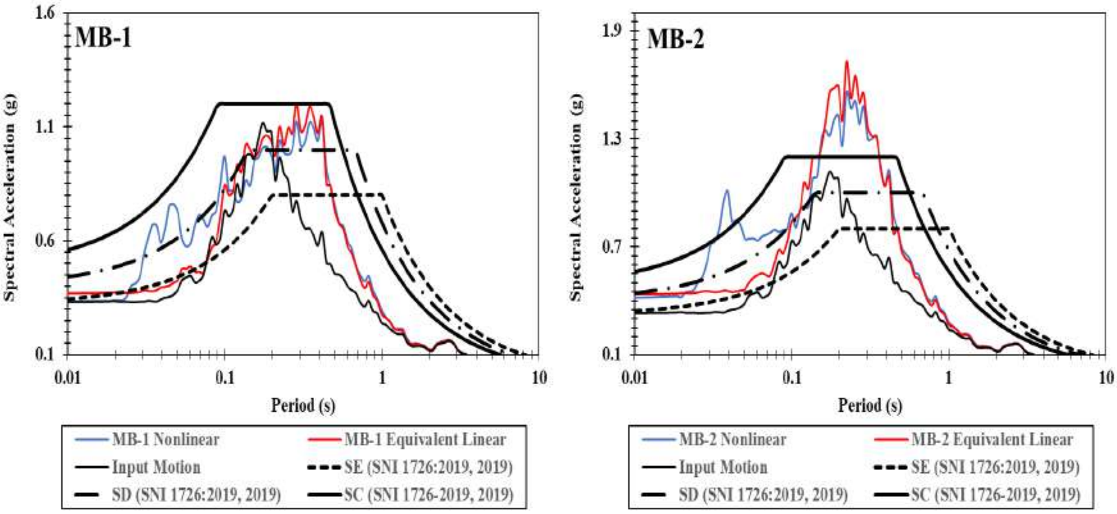
(a) (b)



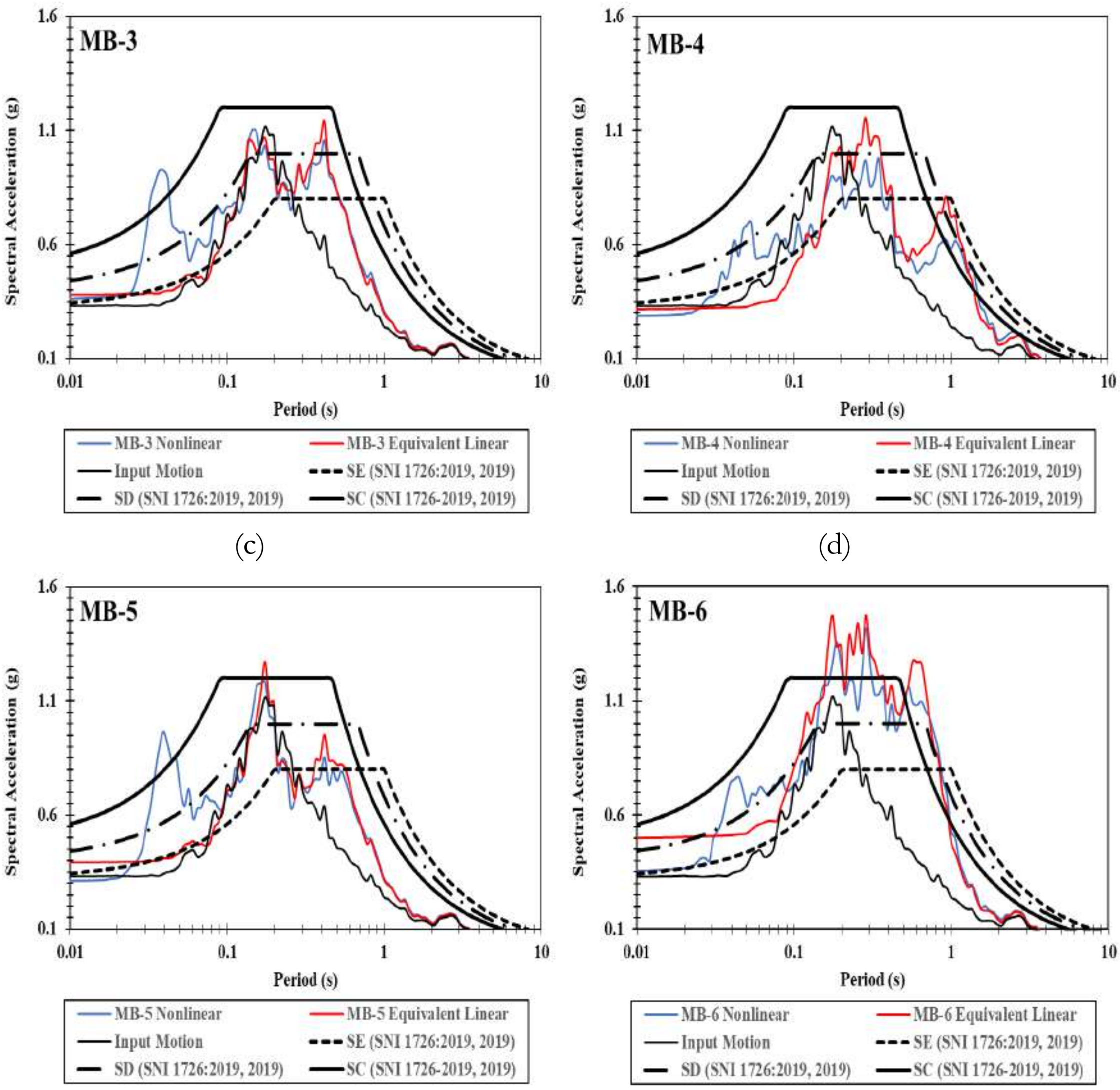
(c) (d)

(e) (f)

Figure 11. Earthquake Acceleration Time History Analysis Results of (a) MB-1, (b) MB-2, (c) MB-3, (d) MB-4, (e) MB-5, and (f) MB-6.



(a) (b)



(c) (d)

(e) (f)

Figure 12. Results of Accelerated Spectral Response Analysis of (a) MB-1, (b) MB-2, (c) MB-3, (d) MB-4, (e) MB-5, and (f) MB-6.

Conclusion

Based on the seismic response analysis results by propagating earthquake waves from the ground to the ground surface, it shows that the deeper a layer of soil is propagated, the smaller the PGA value will be due to differences in soil types and Vs values in each layer. Overall, wave propagation results based on the equivalent linear approach tend to produce more significant maximum accelerations than the nonlinear approach due to the overestimation of shear stress, which also causes the PGA value to be more significant. In addition, the influence of soft layers that have relatively low resistance characteristics causes the magnification of earthquake wave acceleration and amplification factors near the surface. The resulting spectral acceleration at the surface layer shows higher results than the seismic design of Bengkulu City required by SNI 1726:2019. The research location is generally dominated by sandy soil, and building structures have not been considered in this study, so the results of the seismic response design in this study can be a reference for carrying out the construction process in the research location area, especially Muara Bangkahulu Sub-district.

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