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PREDICTION OF MEGATHRUST IMPACT ON SEISMIC RESPONSE IN SELEBAR DISTRICT OF BENGKULU CITY

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Abstract

The Bengkulu City was hit by major earthquakes in 2000 and 2007 with magnitudes of 7.9 Mw and 8.6 Mw. In 2022 BMKG Baai Island, Bengkulu City, said that there is a potential for an earthquake with a maximum magnitude of 8.9. This study was conducted to determine the response of soil layers due to megathrust earthquake wave propagation in Selebar district, Bengkulu City. The study began with field investigations at six points. The seismic response analysis was built based on a one-dimensional wave propagation model with non-linearity. The 2007 Bengkulu-Mentawai earthquake wave with a magnitude of 8.8 Mw was applied as the input wave. PGA, acceleration response spectra, and amplification factors are presented in this study. The resulting PGA ranged from 0.328g - 0.453g. Five points experienced amplification with amplification factors of 1.093 - 1.317. The spectral acceleration has generally exceeded the applicable design spectral acceleration at a period of 0.2 seconds. The spectral accelerations have generally exceeded the applicable seismic design at short periods, with maximum values of 1.27g - 1.64g. So it is necessary to update the seismic design for building planning in Selebar District, Bengkulu City.

Keywords: Earthquake, Seismic Response, Megathrust

Introduction

Earthquakes originating from subduction zones are commonly referred to as Megathrust earthquakes (Nainitania et al., 2021.). A megathrust fault is the interface between a subducting plate and an overriding plate in a subduction zone. (Bilek & Lay, 2018). Megathrust earthquakes produce a considerable amount of coseismic and postseismic lithospheric deformation, including a large number of aftershocks (e.g., Houng et al., 2016 ; Lee & Hong, 2014). The megathrust itself can involve shear zones, and not just a single surface and repeated ruptures of plate boundary contacts can occur on parallel faults within the shear zone. Massive megathrust earthquakes trigger earthquakes around the world in a variety of tectonic environments (e.g., An et al., 2024 ; Peng et al., 2024 ; Takeda et al., 2024 ; Cortez et al., 2023 ; Miyazawa & Santoyo, 2021 ; Hough et al., 2020 ; Philibosian & Meltzner, 2020 ; Yukutake et al., 2019 ; McNamara et al., 2017).

Various seismotectonic environments encircle Bengkulu City, including the Sumatra subduction, Mentawai, and Sumatra faults. These faults and the subduction zone play a significant role in the region's seismic activity, with the potential to trigger earthquakes in Bengkulu City and its surrounding areas. Understanding these seismotectonic conditions is crucial for assessing the earthquake risk in Bengkulu City (Mase et al., 2021). The Sumatra subduction zone is seismically exceptionally dynamic compared to other major subduction zones worldwide. Since 2004, a series of large earthquakes have occurred along the trough, including the 2004 Sumatra-Andaman earthquake of 9.2 Mw, the 2005 Nias-Simeulue earthquake of 8.6 Mw, the 2007 Bengkulu earthquake of 8.6 Mw, the 2010 Mentawai tsunami earthquake of 7.8 Mw, and several moderate and small earthquakes. An extensive fault system crosses the island of Sumatra on the plains of Sumatra. This zone is known as the Sumatra fault system ((Rusydy et al., 2020)).

On August 25, 2022, BMKG Baai Island, Bengkulu City, said that there was a potential earthquake with a maximum strength of 8.9 magnitudes centred in the Mukomuko Regency area (Badan Meteorologi, Klimatologi, dan Geofisika (BMKG), 2022). The earthquake also has the potential to cause a tsunami with waves reaching 15 meters in height. Based on historical records, a large earthquake occurred south of the equator in 1833 with a magnitude of 8.9 and in 1797 with a magnitude of 8.3, causing a tsunami that hit West Sumatra and Bengkulu. Experts predict that the subduction zone will produce another large earthquake with a 200-year return period (Natawidjaya, 2007).

The activities of the Sumatra Subduction Zone, Mentawai Fault, and Sumatra Fault can trigger earthquakes in Bengkulu City and its surrounding areas. Therefore, Bengkulu City is one of the areas in Indonesia that is prone to earthquake disasters. The seismotectonic conditions in Bengkulu City can be seen in Figure 1. Mase (2018) reported that in the last 20 years, there have been two strong earthquakes with magnitudes of up to 8.6 Mw in Bengkulu City. The initial earthquake, registering a magnitude of 7.9 Mw, occurred on June 4, 2000, known as the Bengkulu-Enggano Earthquake. This was followed by a second earthquake of magnitude 8.6 Mw, the Bengkulu-Mentawai Earthquake, on September 12, 2007. Both seismic events resulted in significant consequences, including structural damage to buildings, loss of life, and instances of liquefaction in Bengkulu City.

Selebar district is one of the districts in Bengkulu city. Selebar has an area of 43.35 km^2 and a population of 79,498 (Badan Pusat Statistik Kota Bengkulu, 2022). This area is a developing area that is planned as a sub-city service II with functions as a district government centre, public services, trade and service centres, industrial centres, health, sports centres, and national scale transportation nodes (Peraturan Daerah Kota Bengkulu Nomor 4 Tahun 2021, 2021). Farid and Mase (2020) said that the Selebar district will be used as a trade area, residential area, green open space, and industrial area. Critical facilities in the Selebar district include Fatmawati Soekarno Airport, Fatmawati Soekarno State Islamic University, Bengkulu-Taba Penanjung toll road, and government and private office buildings.

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

Many studies on seismicity have been conducted in Bengkulu City, one of which is a study on seismic response analysis. Seismic response analysis involves the one-dimensional transmission of seismic waves across horizontal layers of soil (Mase & Likitlersuang, 2021). One-dimensional seismic response analysis is an analysis used to solve the vertical propagation of horizontal shear waves through layers (Hashash & Park, 2001.). Seismic waves propagate from the bedrock to the ground surface. Nonlinear soil response analysis must be used to account for the highly nonlinear dynamic properties of the soil (Hashash et al., 2010). This kind of research has been done before but still has some limitations, such as Puri et al., (2018), Misliniyati et al., (2018), Mase (2018), and Likitlersuang et al., (2020) who applied the concept of earthquake wave propagation at a ground depth of 30 m. Mase (2018) Examined the reliability of spectral acceleration in the coastal area of Bengkulu City and concluded that the spectral acceleration for short periods had exceeded the design spectral acceleration. Mase et al., (2022) conducted seismic response research on the Lighthouse View Tower building to observe the health condition of the structure after ten years of standing and found that the actual ground response spectral acceleration was lower than the design spectral acceleration. Misliniyati et al. (2019) conducted a validation study on seismic response, utilising a simulated soil model to analyse a vertical recording image during a significant earthquake event. This study emphasises the need for a comprehensive earthquake wave propagation model to predict accurately. Misliniyati et al. (2019) The non-linear model is the most appropriate method for earthquakes with high seismic acceleration. Farid et al., (2024) investigated seismic response in Muara-Bangkahulu district by comparing linear and non-linear equivalent methods. Agustina et al., (2019) Analysed the seismic response in the central region of Bengkulu City and discovered that the spectral acceleration observed surpassed the design acceleration. Consequently, there is a need to revise the seismic design standards for building planning in Bengkulu City.

Previous seismicity studies were primarily conducted in the coastal and central areas of Bengkulu City, while very few seismicity studies have been undertaken in the Selebar district. Considering the rapid development of the Selebar district and the fact that the central government of Bengkulu City will plan it, it is necessary to conduct seismicity research in the Selebar district. Selebar district, located on the west coast of Bengkulu City, is prone to megathrust earthquakes due to its proximity to the subduction zone between the Indo-Australian and Eurasian plates. The history of major earthquakes that struck Bengkulu in 2000 and 2007 shows that this area is in a zone with a high potential for major earthquakes. Selebar district, with its population density and vital infrastructure, has its own vulnerability to the impact of such earthquakes. Therefore, this study aims to assess the potential for megathrust earthquakes in Selebar district. This research will predict the impact of a megathrust earthquake by looking at the resulting seismic parameters. Seismic analysis was performed with a one-dimensional wave propagation model. This research analysis produces time history acceleration, Peak Ground Acceleration, spectral response acceleration, and amplification factor. This research is expected to provide an overview of the seismic response conditions of the soil layers in Selebar district, Bengkulu City, during a megathrust earthquake. The results of this research can also be an initial step in planning spatial and regional planning based on disaster mitigation in Selebar district, Bengkulu City.

Research Methods

The research was conducted in Selebar district, Bengkulu City. The study was conducted at six points, each point representing one sub-district in Kecamatan Selebar Bengkulu City. The research locations can be seen in Figure 2.

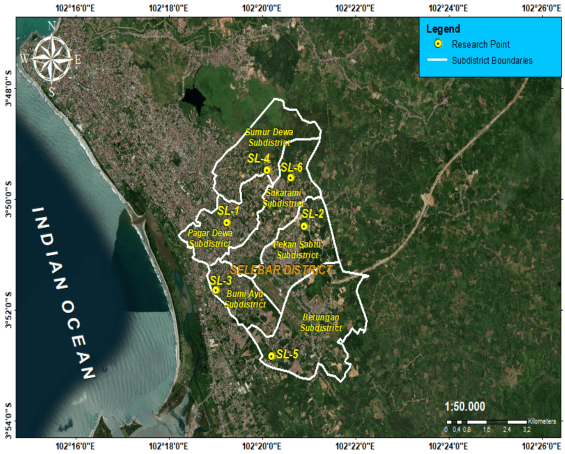


Figure 2. Research location in Selebar district, Bengkulu City

Seismic response analysis is built with a one-dimensional earthquake wave propagation model of a non-linear method. One-dimensional non-linear modelling uses the Pressure Dependent Hyperbolic (PDH) model in this study. This study's one-dimensional seismic wave modelling stage used Deepsoil v6.1 software. The input data required in this step are soil layer data, bedrock depth data, and motion data of the 2007 Bengkulu-Mentawai earthquake scaled 8.8 Mw (Mase, 2017) as input waves, input motion can be seen in Figure 3. The research began with field investigations using microtremor at a predetermined research location. Subsequently, the results were further processed to obtain a description of soil layers, VS (shear velocity), and VP (pressure velocity) in each layer. The soil data can be seen in Figure 4.

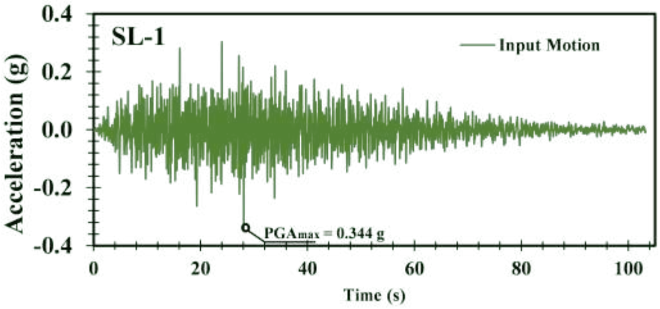
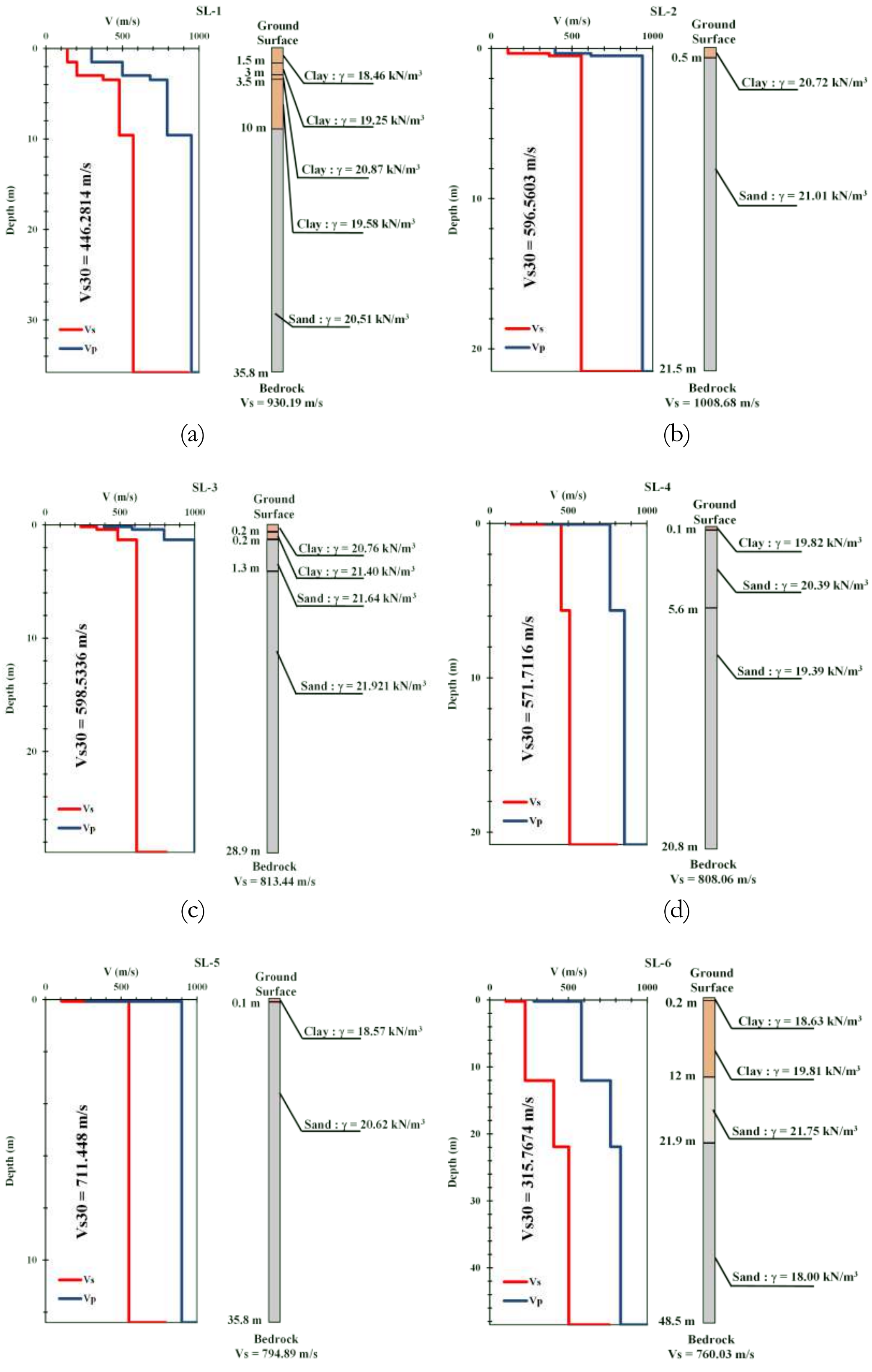


Figure 3. Input Motion (Modified from Mase (2017))



(a) (b) (c) (d) (e) (f)

Figure 4. Soil layer profile, SL-1 (a), SL-2 (b), SL-3 (c), SL-4 (d), SL-5 (e) and SL-6 (f)

The Dynamic parameters and plasticity index (PI) values are also input. Using reference curves, dynamic parameters such as shear modulus (G/Gmax) and damping ratio (ξ) are determined based on the soil type. For cohesive soils, the Vucetic and Dobri (Mase 2017b) G/Gmax curve with a PI limit between 15 and 30 was used, which corresponds to the PI at the study site (Figure 5), while for granular soils, the Seed and Idriss (Mase, 2017b) A G/Gmax curve with an average limit was used (Figure 6). These reference curves were chosen because they can produce higher surface accelerations than the other curves. Figure 6 below briefly shows the stages of analysis used in this research on nonlinear one-dimensional seismic wave modelling using the Pressure Dependent Hyperbolic model.

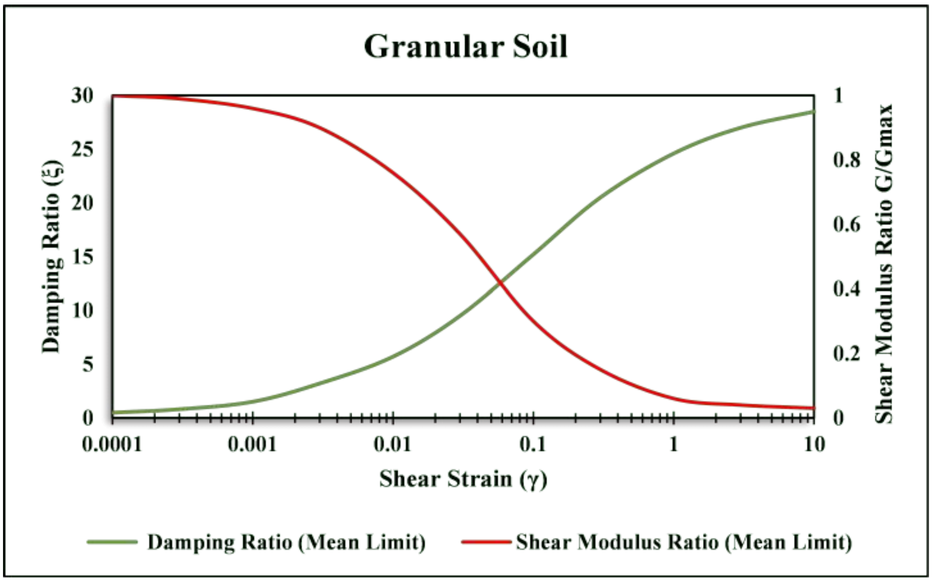


Figure 5. G/Gmax curve and damping ratio for granular soils (Modified from Mase (2017b))

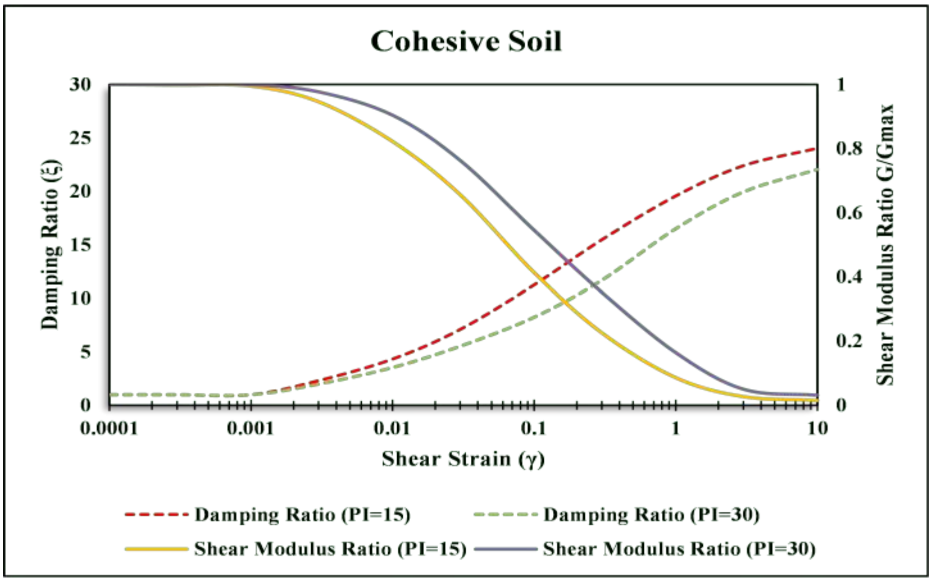
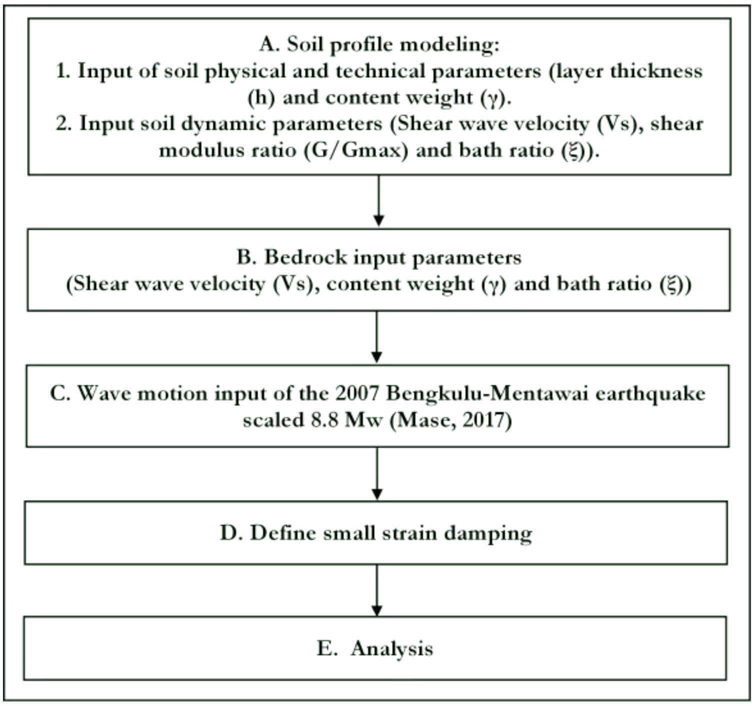


Figure 6. G/Gmax curve and damping ratio for cohesive soils (Modified from Mase (2017b))



A. Soil profile modeling:
1. Input of soil physical and technical parameters (layer thickness (h) and content weight (γ).
2. Input soil dynamic parameters (Shear wave velocity (Vs), shear modulus ratio (G/Gmax) and bath ratio (ξ)).

B. Bedrock input parameters (Shear wave velocity (Vs), content weight (γ) and bath ratio (ξ))

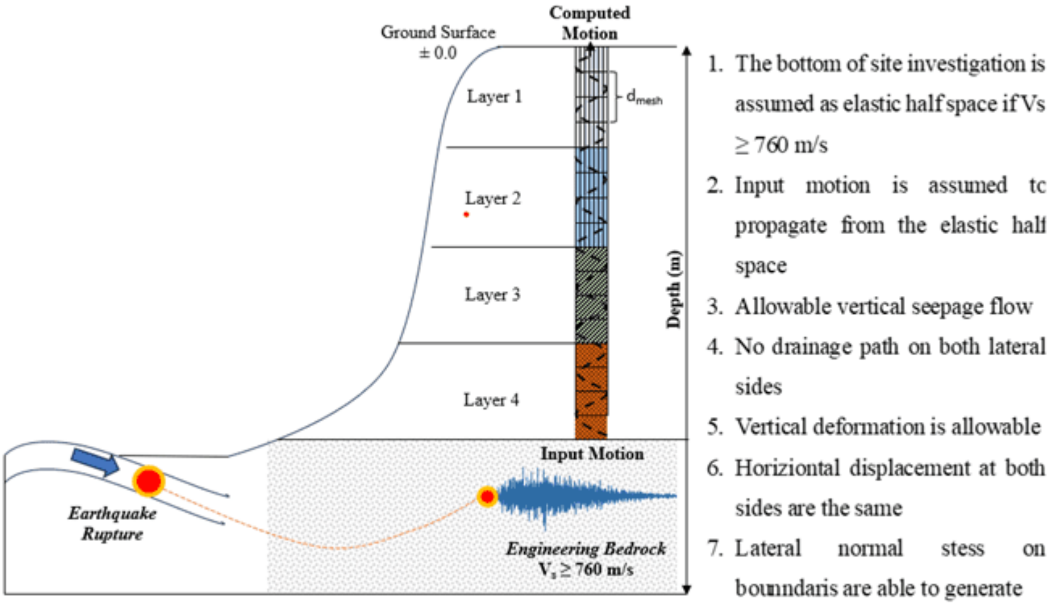
C. Wave motion input of the 2007 Bengkulu-Mentawai earthquake scaled 8.8 Mw (Mase, 2017)

D. Define small strain damping

E. Analysis

Figure 7. Flowchart of one-dimensional seismic wave modelling stages nonlinear pressure dependent hyperbolic model

The modelling in Figure 8 illustrates a one-dimensional seismic response analysis, where the soil layer is modelled as a soil column that is vibrated horizontally by the input motion. The primary outcomes of a one-dimensional seismic ground response analysis encompass the time history of ground motions, spectral accelerations, and amplification factors.



1. The bottom of site investigation is assumed as elastic half space if Vs ≥ 760 m/s
2. Input motion is assumed tc propagate from the elastic hali space
3. Allowable vertical seepage flow
4. No drainage path on both lateral sides
5. Vertical deformation is allowable
6. Horiziontal displacement at both sides are the same
7. Lateral normal stess on boundaris are able to generate

Figure 8. The scheme of one-dimensional seismic response analysis (Modified from Sari et al., (2024))

Research Results and Discussion

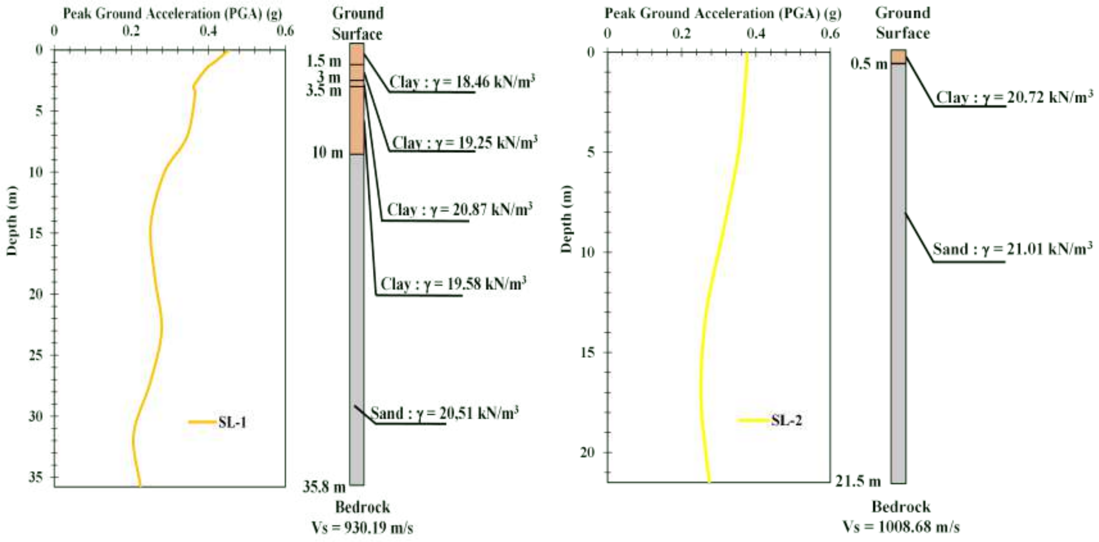
Maximum Acceleration Profile and Amplification Factor

The PGA value is used to determine the level of earthquake risk; the higher the PGA value, the more potential for damage. Fathani et al., (2008) mentioned that the PGA value in 0.3g-0.4g is included in the high risk, and the PGA value > 0.4g is included in the very high risk. The resulting PGA value on the surface ranges from 0.328g - 0.453g; four points are included in the high earthquake risk and two in the very high earthquake risk. The interpretation of the maximum acceleration (PGAmax) profile is presented in Figure 9.

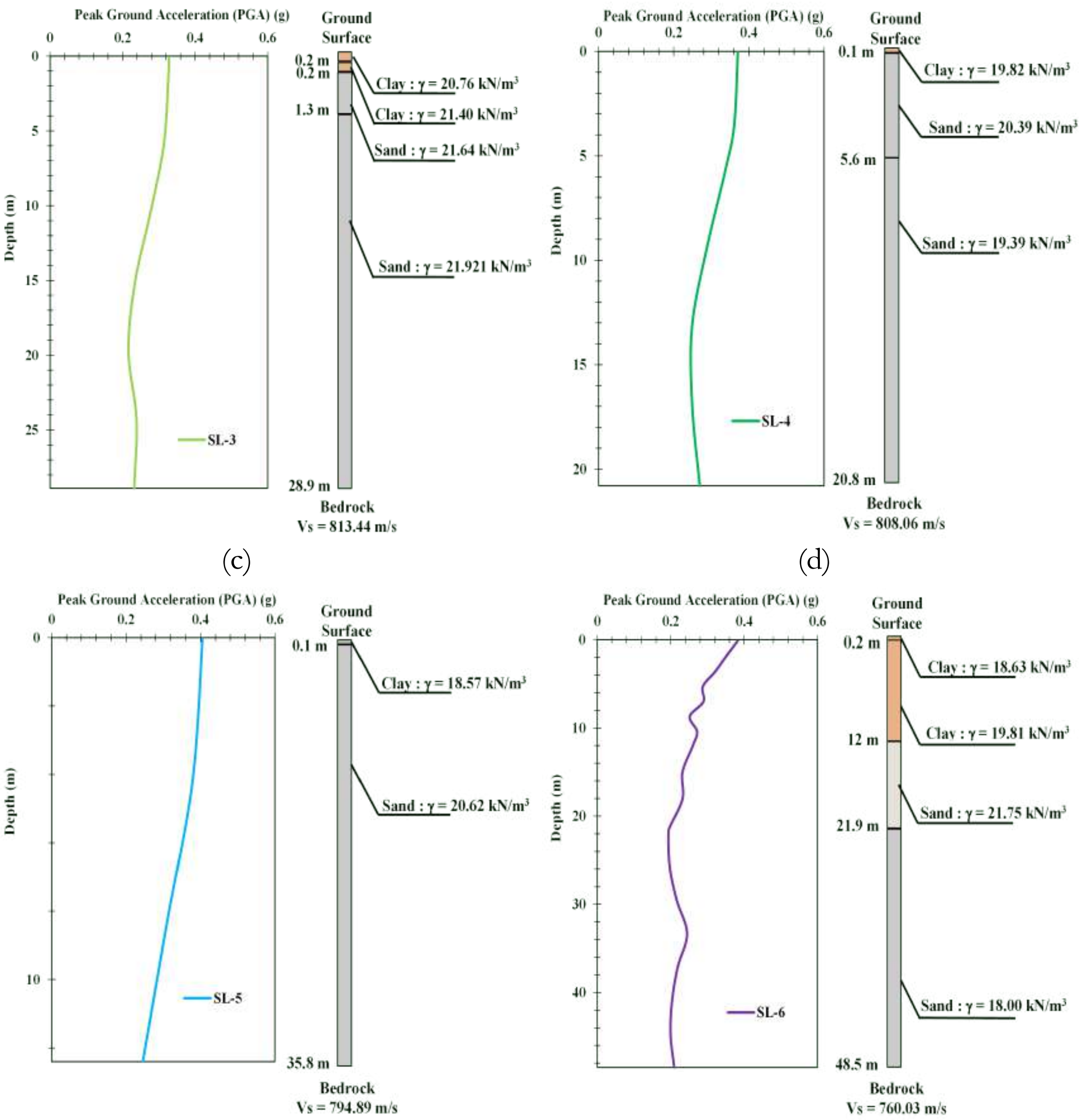
This high PGA value aligns with the geological formations in the Selebar district. Farid and Mase (2020) said that the geological conditions of the Selebar district are dominated by alluvium terraces (Qat). The Qat formation has a high seismic vulnerability index, making it prone to earthquake shaking and liquefaction (Sugianto et al., 2021). Moreover, the Qat geological formation has elastoplastic dynamic properties that have the potential to cause fractures covering 32.84% of the Bengkulu City area. (Sugianto & Farid, 2017).

The wave almost constantly propagates from the sandy soil, starting to strengthen when it reaches the clay soil to the ground surface. This can be influenced by the resistance of sand affected by Vs30; the more significant the Vs30, the more complex the soil layer. This is similar to what was found by Sari et al., (2024) who examined the seismic response in Kampung Melayu District, Bengkulu City.

The amplification factor is obtained by dividing the PGAmax at the surface by the input PGAmax. Generally, the ground motion is amplified by about 1.093 to 1.317, except at point SL-3, which experienced a deamplification of 0.951 (Table 1). Deamplification can occur due to the bedrock's shallow depth and the medium soil site class, which causes the attenuation of earthquake waves to the surface to be small. Amplified soils tend to amplify the intensity of earthquake shaking, which can result in more severe damage to the infrastructure on top of them.



(a) (b)



(c) (d)

(e) (f)

Figure 9. Maximum acceleration (PGAmax) profile SL-1 (a), SL-2 (b), SL-3 (c), SL-4 (d), SL-5 (e), SL-6 (f)

Table 1. Amplification Factor of Each Site Investigation

SL-1	SL-2	SL-3	SL-4	SL-5	SL-6
1.317	1.093	0.951	1.155	1.174	1.111

Spectral Acceleration

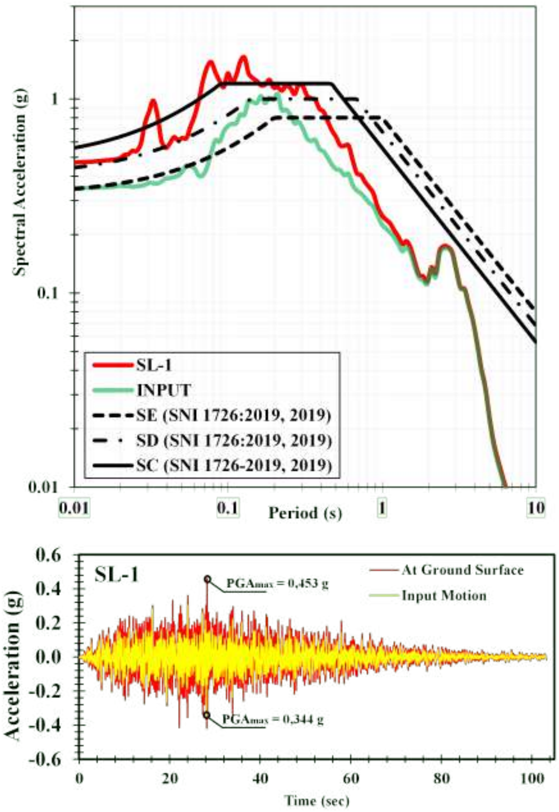
A comparison of the spectral acceleration resulting from the seismic response with the design spectra at ground level is presented in Figure 10. In general, the spectral acceleration of the seismic response has exceeded the design spectral acceleration, especially at 0.2 seconds.

The most considerable spectral acceleration is found at point SL-1, and the shear wave velocity influences this in the bedrock at 930.19 m/s. The spectral acceleration at the ground surface will tend to have a larger amplitude value as the Vs of the bedrock increases (Misliniyati, 2022). Soil site class and depth of bedrock also affect the magnitude of spectral acceleration at the surface. The spectral acceleration at the surface tends to increase as the bedrock elevation becomes shallower (Misliniyati, 2022). Vs30 can determine the soil site class; the soil has Vs30 in the range of 175m/s - 350m/s is classified as medium soil, and 350m/s - 750m/s is classified as hard soil

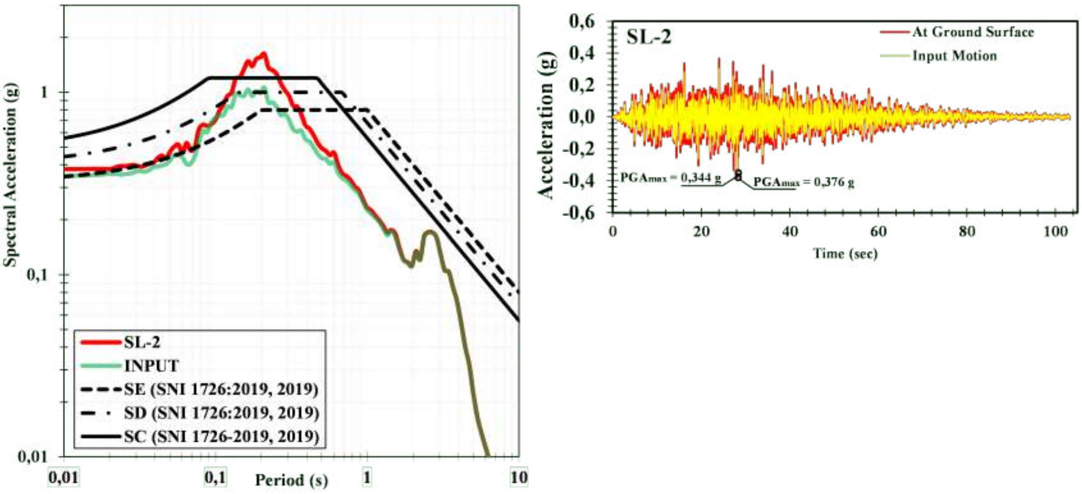
(SNI 1726-2019, 2019). Click or tap here to enter text.Therefore, at this point, SL-1 is classified as hard soil. The bedrock depth is only 35m, and the challenging soil site class causes the damped wave energy during wave propagation to be minor, which causes the spectral acceleration at the surface to be significant. The slightest spectral acceleration is at point SL-3; this is influenced by the medium soil site class at point SL-3, which causes considerable damping of earthquake waves during wave propagation.

The results showed that the spectral acceleration at each point peaked at a period of 0.2 seconds (short period). By estimating the natural period with T equal to 0.1n (n is the number of floors), the impact of earthquake hazards can be predicted based on the number of floors of the building. (International Code Council, 2006). The SA of 0.2 s is useful for predicting the ground response received by low-storey buildings in the form of resonant periods on the 1-2-storey floors of the building. The SA of 1 s represents the ground response received in high-storey buildings. (Mase, 2020).

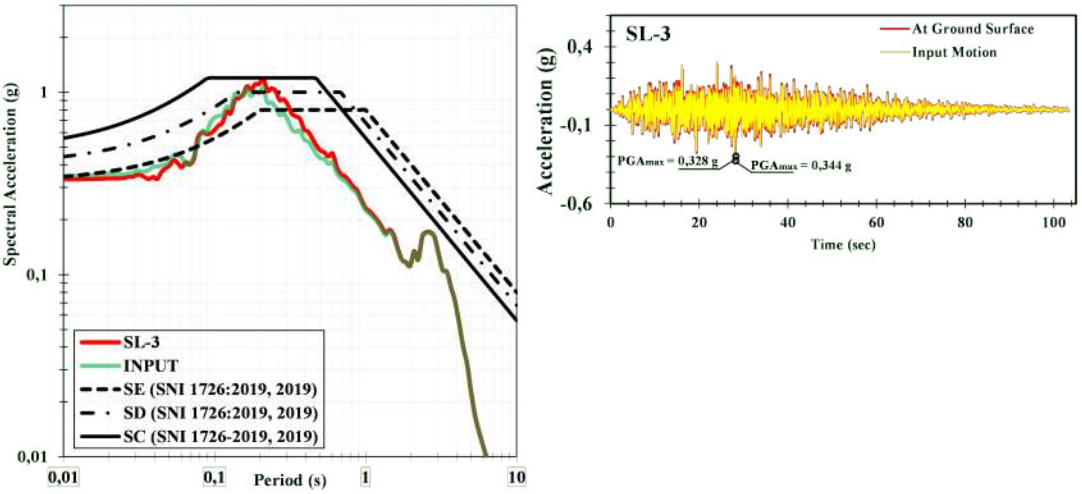
The spectral accelerations have generally exceeded the applicable seismic design at short periods, with maximum values of 1.27g - 1.64g. It can be concluded that damage will occur mostly in low-floor buildings. The spectral acceleration at points SL-1, SL-2, SL-4, SL-5, and SL-6 has exceeded the spectral acceleration of SNI 1726:2019 (2019) in all classes of soil sites; therefore, it is necessary to review the low-floor buildings built at that location.



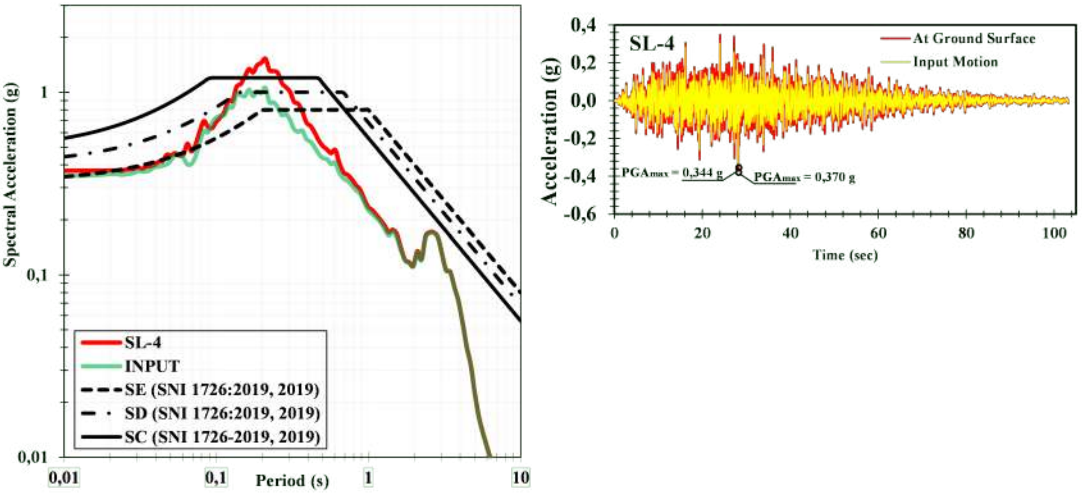
(a)


Spectral Acceleration (g)
Period (s)
0,01
0,1
1
10
SL-2
INPUT
SE (SNI 1726:2019, 2019)
SD (SNI 1726:2019, 2019)
SC (SNI 1726-2019, 2019)
SL-2
At Ground Surface
Input Motion
Acceleration (g)
Time (sec)
PGAmax = 0,344 g
PGAmax = 0,376 g

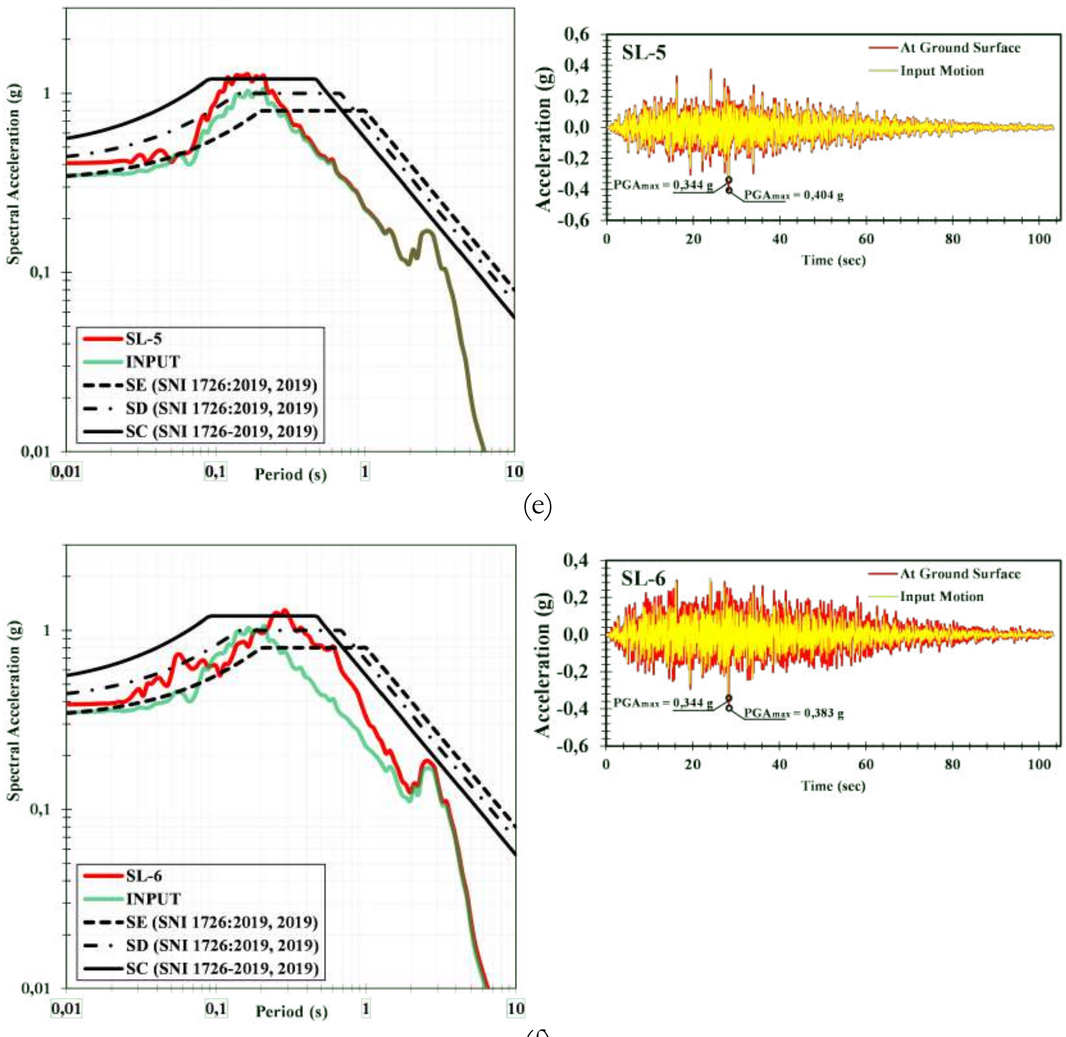
(b)


Spectral Acceleration (g)
Period (s)
0,01
0,1
1
10
SL-3
INPUT
SE (SNI 1726:2019, 2019)
SD (SNI 1726:2019, 2019)
SC (SNI 1726-2019, 2019)
SL-3
At Ground Surface
Input Motion
Acceleration (g)
Time (sec)
PGAmax = 0,328 g
PGAmax = 0,344 g

(c)


Spectral Acceleration (g)
Period (s)
0,01
0,1
1
10
SL-4
INPUT
SE (SNI 1726:2019, 2019)
SD (SNI 1726:2019, 2019)
SC (SNI 1726-2019, 2019)
SL-4
At Ground Surface
Input Motion
Acceleration (g)
Time (sec)
PGAmax = 0,344 g
PGAmax = 0,370 g

(d)



(e)

(f)

Figure 10. Spectral acceleration comparison SL-1 (a), SL-2 (b), SL-3 (c), SL-4 (d), SL-5 (e), and SL-6 (f)

Conclusion

The resulting PGA values range from 0.328g - 0.453g. These results show four villages have a high earthquake risk and two very high. Input waves tend to experience magnification during earthquake wave propagation, and this can be seen in five points that experience amplification with an amplification factor of 1.093 - 1.317. Deamplification occurred at one end with a deamplification factor of 0.951. This could be due to the challenging soil site class, which causes considerable damping during the propagation of earthquake waves from the bedrock. In addition, the value of shear velocity (Vs) and the depth of bedrock can also cause deamplification. The results show that the design spectral accelerations can no longer cover the accelerations generated by megathrust earthquake waves, especially at a period of 0.2 seconds. The spectral accelerations have generally exceeded the applicable seismic design at short periods, with maximum values of 1.27g - 1.64g. The spectral acceleration of the seismic response analysis has exceeded the design spectral acceleration for all site classes at five points and two site classes (soft soil and medium soil) at one point. Therefore, future building structures should be constructed using local spectral acceleration in the Selebar district.

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