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# Analysis of Soil Seismic Response in Bengkulu Using Mentawai Earthquake Scenario

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## ABSTRACT

*Bengkulu is a province that has a high earthquake hazard level due to the influence of the Sumatra subduction zone, the Mentawai megathrust, and active fault systems. Previous studies have mostly focused on regional earthquake hazard assessment, whereas site-specific studies of soil seismic response in Bengkulu remain lacking. The purpose of this study is to evaluate the seismic response of Bengkulu's soil using the Mentawai earthquake scenario by combining the $Vs_{30}$ parameter with one-dimensional nonlinear soil response analysis. The Mentawai scenario was selected because the region is a potential seismic gap that may potentially affect Bengkulu due to its geographical proximity. Ground motion input was developed using Cone Penetration Test (CPT) data, $Vs_{30}$ values, NGA-Subduction analysis, and spectral matching for four study sites: Mukomuko, Ketahun, Ratu Samban, and Manna. The results of the study show that the Peak Ground Acceleration (PGA) values at the surface are in the range of 0.0002 to 0.0009 g with amplification factors from 1.20 to 3.15. The low PGA values indicated attenuation due to the earthquake source distance of 326-602 km. The results of this study indicate that local soil properties have an important role in amplification characteristics and surface seismic response and therefore can provide useful information for earthquake mitigation and planning of earthquake-resistant infrastructure in Bengkulu Province.*

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## INTRODUCTION

Indonesia is a highly earthquake-prone region due to its high seismic activity. Over the last two decades, a number of significant events, including the 2004 Aceh earthquake, the 2006

Yogyakarta earthquake, the 2007 Bengkulu-Mentawai earthquake, the 2009 Padang earthquake, and the 2018 Palu earthquake, have caused widespread damage to infrastructure and numerous casualties [1]. These events show that the effects of earthquakes are influenced not only by the earthquake's source but also by local ground conditions, which can amplify shaking.

This condition reflects the complexity of the tectonic structure of Indonesia due to the interaction of the Indo-Australian and Eurasian plates [2]. The Mentawai Zone is part of the active Sunda subduction system, which is one of the main sources of megathrust earthquakes in Indonesia [3]. Bengkulu Province is situated in an active seismic area, influenced by the Sumatra Fault, the Mentawai Fault, and the Sumatra subduction zone [4][5, 6]. The 2000 $M_w$ 7.9 Bengkulu-Enggano earthquake and the 2007 $M_w$ 8.6 Bengkulu-Mentawai earthquake generated strong shaking and caused heavy damage in the Bengkulu region. [7–12].

These events revealed that Bengkulu is highly susceptible to megathrust earthquakes and requires site-specific seismic response studies to assess how local soil conditions influence surface ground motion.

Geologically, the Bengkulu region is dominated by young deposits, including alluvium, alluvial terraces, and swamp deposits, as well as hard rocks such as andesite and the Bintunan Formation [13][14, 15]. These variations in the geological conditions affect the propagation of seismic waves and the soil response at each site [16]. Soil dynamic parameters, especially shear-wave velocity (Vs), density, and damping, govern the propagation of seismic waves. In soft soil, the low Vs results in greater amplification due to lower soil stiffness and a larger impedance contrast between layers. Resonance can also occur when the dominant frequency of an earthquake approaches the soil's natural frequency, thereby increasing the surface acceleration.

Previous studies in the Sumatra and Bengkulu regions have generally used a Probabilistic Seismic Hazard Analysis (PSHA) approach, which produces regional hazard levels but has not conducted seismic soil response based on local conditions in detail. The applications of $Vs_{30}$ parameters, spectral response analysis, and the Mentawai earthquake scenario are still limited in Bengkulu. The ongoing development of infrastructure in Bengkulu requires a site-specific seismic response analysis to obtain a more representative ground-motion estimate than a regional approach.

In this study, the adopted scenario is the Mentawai Megathrust earthquake scenario, which still retains considerable energy and can generate large earthquakes in the future [17], [18]. The Mentawai scenario is selected because a seismic gap could release the energy of a major earthquake in the future. Bengkulu is also prone to the impact of the earthquake because it is close to the epicenter. A scenario-based approach has been chosen because it allows to evaluate possible earthquake events that are not historically recorded. In this study, the $Vs_{30}$ parameter and the site-specific spectral response analysis are used to study the seismic response of the ground in the Bengkulu region for the Mentawai earthquake scenario.

## RESEARCH METHODS

### Study Area and Site Investigation

This research was carried out in four coastal locations in the Bengkulu Province, Mukomuko (GM-1), Ketahun (GM-2), Ratu Samban (GM-3), and Manna (GM-4) as shown in Figure 1 the site selection of the sites was based on the geographical distribution, the proximity to the source of the Mentawai earthquake, the variation of the stiffness of the soil and the propagation of the seismic waves. Soil profiles and dynamic parameters for seismic response analysis were defined by identifying local soil properties using.

Cone penetration Test (CPT) data and $Vs_{30}$ values. Figure 2 shows that most of the sites are indicated as having low-to-moderate-stiffness soils, which can lead to amplification of seismic waves. These parameters were used as input for the modeling.

### Seismic Site Response Analysis

The seismic response analysis is performed in one-dimensional (1D) to investigate the influence of local soil conditions on the ground motions during earthquakes. The method simulates the vertical propagation of shear wave from bedrock to the surface through horizontally uniform soil layers [19–21], [20], and [21]. The 1D seismic response analysis accounts for the dynamic properties of the soil, including variations in shear modulus and damping induced by cyclic earthquake loading. Shear modulus, damping ratio, and Vs characterize the degree of seismic wave amplification in each soil layer. To better reflect the actual soil conditions, the reduction in soil stiffness and the increase in damping due to cyclic strain are considered nonlinear effects.

A nonlinear approach was used with CPT data collected to a depth of about 30 m to develop soil profiles, determine the shear wave velocity (Vs), and establish site classification [22]. Soil layer profiles and available soil dynamic characteristics, such as shear-wave velocity in each layer, are compiled from CPT data. The maximum shear modulus ($G_{max}$) and site categorization based on the $Vs_{30}$ value are among the soil dynamic parameters subsequently determined from these profiles. The main input for the analysis of seismic soil reaction is these characteristics. This analysis uses historical ground acceleration data [19].


Figure 1. Location Map

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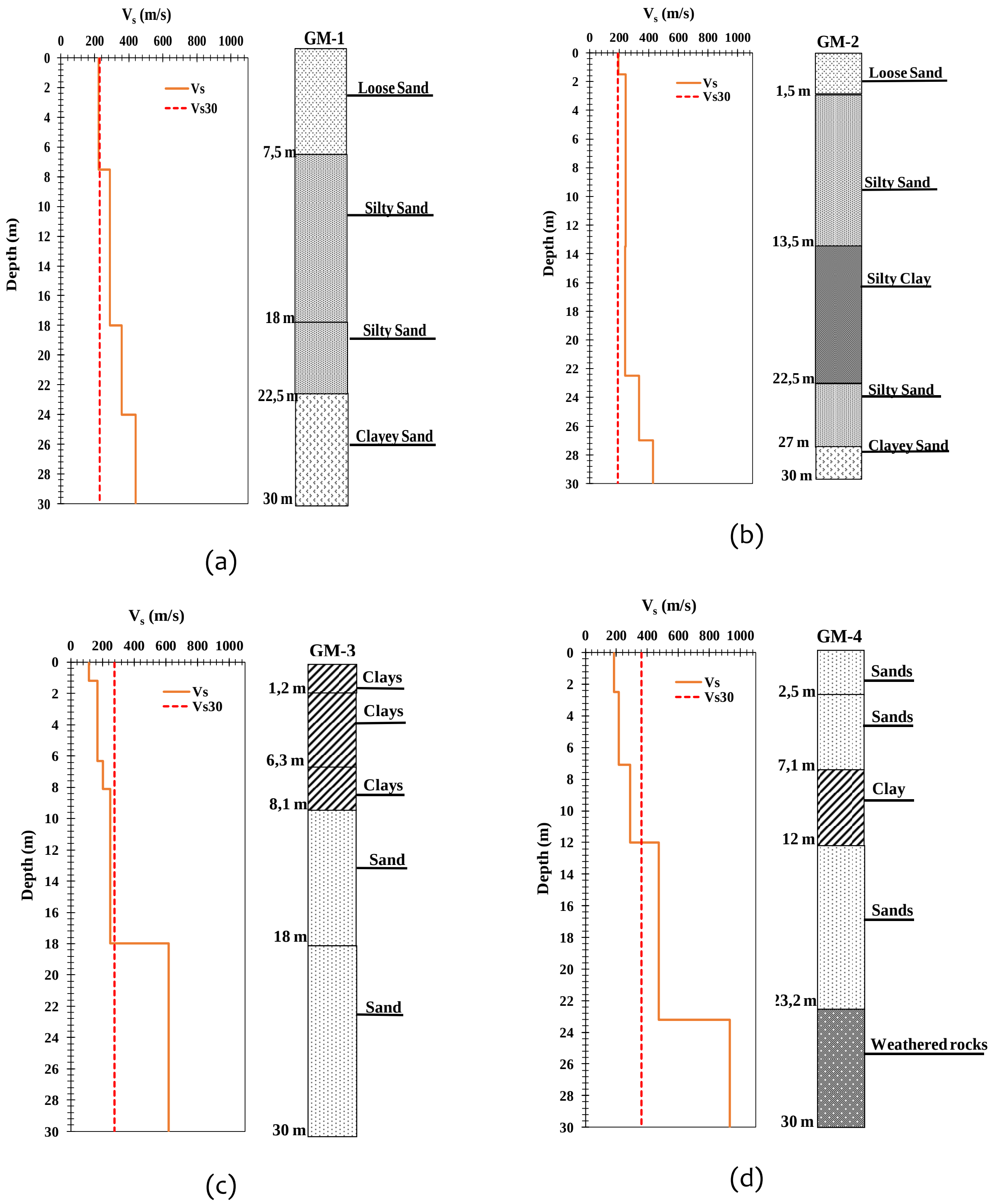


Figure 2. Survey data for locations (a) GM-1, (b) GM-2, (c) GM-3 and (d) GM-4

The ground acceleration values from the analysis were converted from m/s² to gravitational acceleration units (g) by dividing by 9.81 m/s², so that Peak Ground Acceleration (PGA) could be interpreted consistently.

$$d = \frac{Vs}{4f_{max}} \tag{1}$$

Where d is the mesh size, Vs is the shear wave velocity (m/sec), and $f_{max}$ is the maximum frequency. This formula ensures that the element sizes in the soil model are sufficiently large to accurately capture the propagation of seismic waves. The soil amplification factor is determined by the ratio of the maximum ground acceleration to the input acceleration at the bedrock. This parameter is used to assess the degree of ground-motion amplification due to local soil conditions on seismic wave propagation [11]. The amplification factor is calculated using the following equation:

$$AF = \frac{PGA_{surface}}{PGA_{input}} \quad (2)$$

In this equation, *AF* is the amplification factor, $PGA_{surface}$ is the peak ground acceleration at the surface (g), and $PGA_{input}$ is the peak ground acceleration at the bedrock (g).

**Earthquake Ground Motion Scenario**

In this study, the earthquake source is assumed to be located in the Mentawai segment of the Sunda subduction zone, an active megathrust region in Indonesia [24]. The earthquake magnitude used is $M_w$ 6.1, based on the Mentawai earthquake that occurred on September 11, 2022, at a depth of approximately 10 km. This event is classified as a shallow subduction earthquake with a thrust fault mechanism, which is geologically consistent with the characteristics of the Mentawai megathrust.

The earthquake scenario has a magnitude of $M_w$ 6.1 and a depth of 10 km, making it a shallow earthquake that could affect the Bengkulu region. The distance from the earthquake source to the study area is measured in terms of Joyner-Boore distance (*R*JB) and the rupture distance (*R*rup). The *R*JB values for each site are 326 km (GM-1), 439 km (GM-2), 507 km (GM-3), and 602 km (GM-4), resulting in considerable attenuation of seismic waves as they propagate. The $Vs_{30}$ values at each site are 228 m/s, 191 m/s, 276 m/s, and 364 m/s, respectively, indicating that the area is dominated by soft-to-moderately stiff soils.

The NGA-Subduction model was chosen because it effectively captures the relationship between earthquake magnitude, source distance, and soil conditions ($Vs_{30}$) in estimating ground motion parameters, including PGA and spectral response. The results from the earthquake source analysis serve as the target spectrum for the spectral-matching process, which produces ground-acceleration records that reflect both the earthquake characteristics and local ground conditions. The input acceleration records, comprising HNN, HNE, and HNZ

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components, are then used as input data in the seismic response analysis. Low $Vs_{30}$ values at certain sites, such as Ketahun and Mukomuko, indicate a greater potential for ground-motion amplification than at locations with stiffer soils. Earthquake source parameters and soil conditions are inputs for ground acceleration analysis.

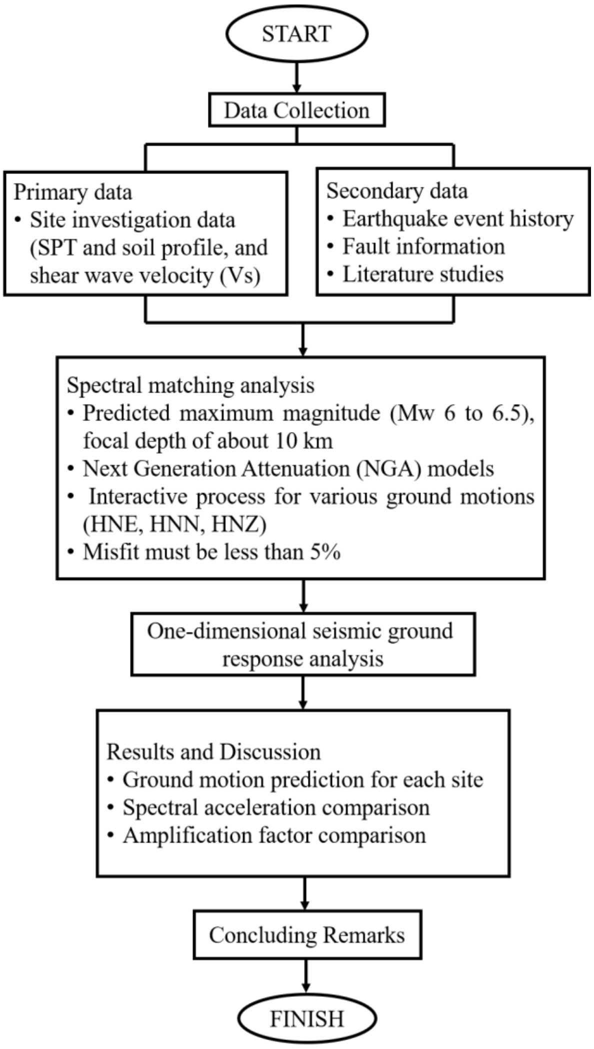


Figure 3. Research Framework

The response spectrum obtained from this analysis is subsequently used as the target in the spectral matching process with software-independent description to generate acceleration records that align with the characteristics of the earthquake source and local soil conditions. The input acceleration records, comprising the HNN, HNE, and HNZ components, serve as input to the spectral matching process.

**Research Framework**

The research methodology used in this study is presented in Figure 3 the first step of this study is to develop the Mentawai Earthquake scenario as a potential seismic hazard source in the Bengkulu Province. The input ground motion was generated using an iterative spectral-matching process based on three strong-motion records to obtain a representative acceleration spectrum with a mismatch of less than 5%. These spectra were then converted to time histories of ground acceleration for input to the analysis. Then, a one-dimensional seismic ground response analysis was carried out using a pressure-dependent hyperbolic soil model, with the key parameters being soil layer thickness, unit weight (γ), shear wave velocity (Vs), and soil dynamic parameters. The results of the analysis in the form of time histories of acceleration, response spectra, and amplification factors were used to assess the characteristics of soil response in the study area and to support studies on earthquake risk mitigation in Bengkulu Province.

## FINDINGS AND DISCUSSION

### Characteristics of Ground Motion Input

Table 1 presents the ground-motion characteristics and spectral-matching results for each study location (GM-1 through GM-4). The results showed that all ground motion data were matched with relatively low misfit values. The ground motion record chosen for the seismic response analysis was the one with the lowest misfit value that did not exceed the 5% criterion, as it was considered to best fit the target spectrum. At GM-1, the HNE, HNN, and HNZ components were well aligned with the target spectrum. The fit of components differed among the study sites, but similar conditions were observed at GM-2, GM-3, and GM-4. The restored records showed good convergence and were suitable for use as input data for seismic ground response analysis. The spectral matching technique was iteratively applied using software-independent description in order to match the spectrum of the earthquake recording to the target spectrum, preserving the signal's main characteristics. The result of the adjustment showed that the waveform modification did not change the signal's basic shape, main amplitude, or duration.

Table 1. Summary of spectral matching results

| Sites | Ground Motions | Matching Condition | Average Misfit |
|---|---|---|---|
| GM-1 | HNE | Converged | 2.8 |
| | **HNN** | **Converged** | **1.6** |
| | HNZ | Converged | 2.0 |
| GM-2 | **HNE** | **Converged** | **3.3** |
| | HNN | Converged | 5.3 |
| | HNZ | Converged | 5.9 |
| GM-3 | HNE | Converged | 4.4 |
| | **HNN** | **Converged** | **3.2** |
| | HNZ | Converged | 4.3 |
| GM-4 | HNE | Converged | 4.0 |
| | HNN | Converged | 5.6 |
| | **HNZ** | **Converged** | **3.6** |

A Mentawai earthquake scenario with a moment magnitude ($M_w$) of 6.1 was selected because the Mentawai region is an active seismic source within the Sumatra subduction zone that has the potential to impact the Bengkulu area. This scenario was chosen to reflect realistic earthquake conditions based on regional seismotectonic characteristics and to assess how local soil conditions influence seismic response in the study area. Figure 4 displays the results of the spectral acceleration analysis using the NGA Subduction model. The findings show that

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differences in spectral acceleration at each site are strongly influenced by both the distance to the earthquake source (*RJB*) and local soil conditions. Increased distance results in wave energy attenuation, whereas soft soils lead to greater amplification of seismic waves.

Figure 5 compares spectral matching results for GM-1 through GM-4. The graph shows that, across all study sites, the matched spectra closely resemble the target spectra, demonstrating strong agreement. These findings indicate that the selected ground-motion records are suitable for seismic ground-response analysis.

Figure 6 displays the ground acceleration time histories for each location. Differences in signal amplitude and duration reveal that local soil conditions and the paths of wave propagation play significant roles in shaping the resulting ground-motion response.

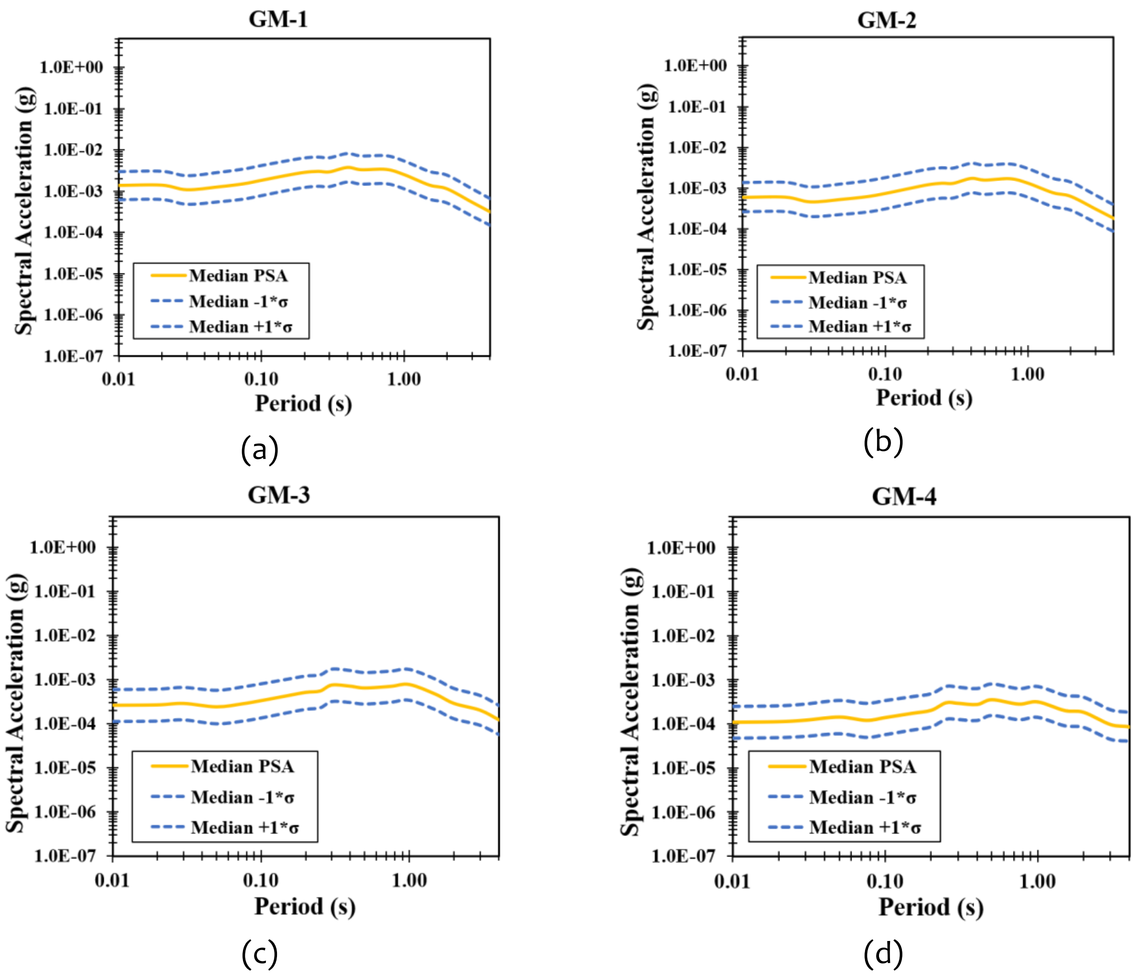


Figure 4. shows the spectrum acceleration analysis results based on NGA-Subduction at (a)GM-1, (b)GM-2, (c)GM-3, and (d)GM-4.

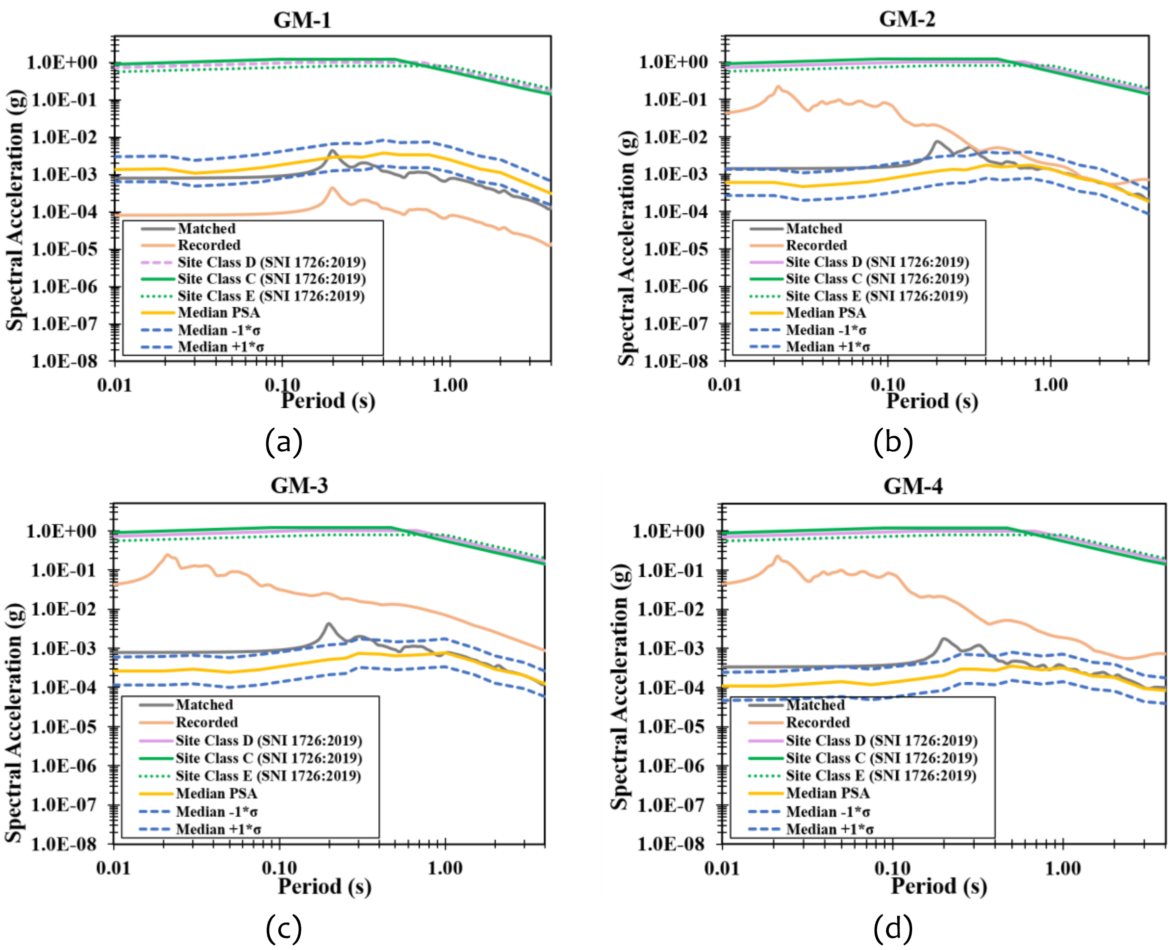


Figure 5. Comparison of spectral matching results for GM-1, GM-2, GM-3, and GM-4.

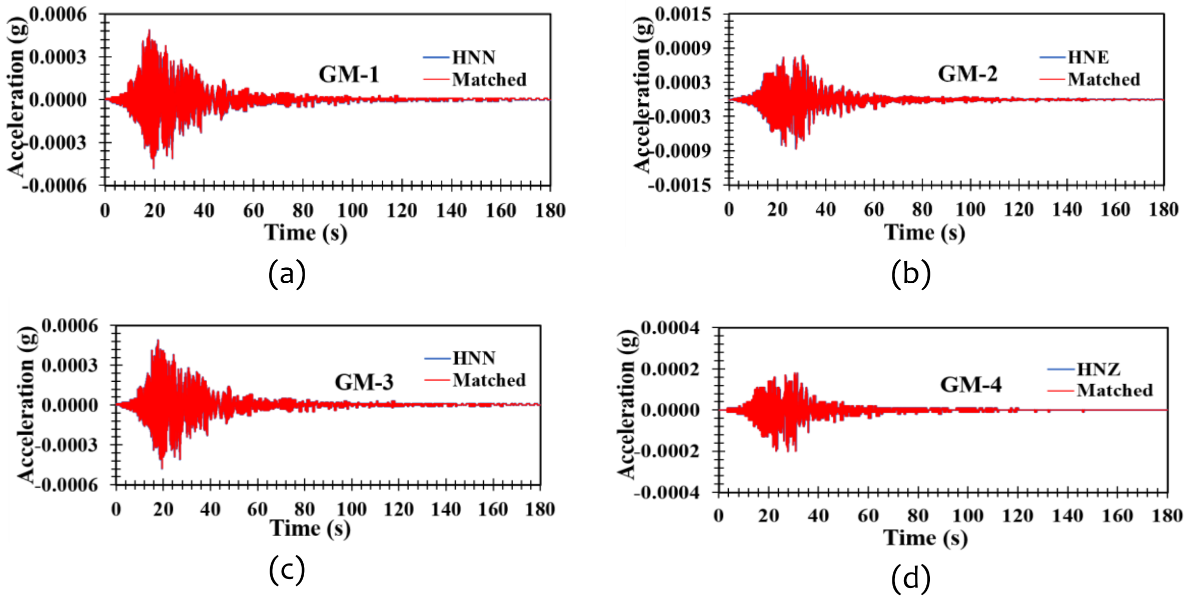


Figure 6. Ground motion based on matching results for locations (a) GM-1, (b) GM-2, (c)GM-3, and (d) GM-4

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**Soil Seismic Response Analysis**

Each research location in Bengkulu Province has a different ground acceleration, according to the findings of the one-dimensional seismic response analysis. Peak Ground Acceleration (PGA) readings at ground level show variations in seismic response influenced by the characteristics of earthquake wave propagation and local soil conditions.

It is important to consider these comparatively low PGA values in relation to the characteristics of the earthquake scenario. With *RJB* values ranging from 326 km to 602 km, the great distance from the earthquake source results in significant attenuation of seismic wave energy during propagation to the research locations, even though the earthquake magnitude is categorized as moderate. As a result, the low PGA value reflects the combined effects of magnitude, source distance, and wave propagation characteristics in the study scenario, rather than a low earthquake hazard potential.

The ground surface response at each site is shaped by local soil properties, particularly the $Vs_{30}$ value. Sites with lower $Vs_{30}$ values generally exhibit greater amplification than those with higher $Vs_{30}$ values. At the study locations, Ketahun (191 m/s) and Mukomuko (228 m/s) demonstrated higher amplification potential than Manna (364 m/s), which has relatively stiffer soil.

During certain periods, especially in the medium- to long-term range, some sites exhibited increased spectral acceleration at the ground surface. This indicates the potential for resonance between the frequency of the earthquake waves and the soil's natural frequency [25].

Although GM-2 had the highest PGA value among the locations, the analysis reveals that GM-3 experienced greater amplification over a specific period. This shows that the magnitude of the input PGA does not necessarily correspond directly to the level of ground-surface amplification. Seismic response at ground level is influenced by the interaction between earthquake motion characteristics and local subsurface conditions, including sediment layer thickness, soil stiffness, and the alignment between the dominant frequency of seismic waves and the ground's natural frequency. In the GM-3 event, a resonance phenomenon likely occurred, amplifying seismic wave energy as it propagated through certain soil layers, resulting in greater amplification than in the GM-2 event despite GM-3 having a lower initial PGA.

Furthermore, local geological conditions and subsurface stratigraphy significantly influence the seismic response at each study site. Sites with softer sedimentary layers and lower Vs30 values generally experience greater wave amplification than those with denser or stiffer soils. Table 2 presents the input PGA values, ground surface PGA, and amplification factors for each location. The amplification factor is calculated as the ratio of the maximum ground surface acceleration to the input acceleration at the bedrock. The results reveal variations in amplification across sites, reflecting the influence of local soil properties and subsurface layer characteristics.

Figure 7 compares spectral acceleration and acceleration time histories for each study site. The analysis demonstrates that variations in acceleration amplitude and response spectrum shape are influenced by local soil conditions and seismic wave propagation characteristics at each location. Sites with softer soils generally exhibit higher spectral responses than those with stiffer soils. To further support the interpretation, these results were compared with historical earthquakes in Bengkulu, such as the 2000 earthquake ($M_w$ 7.9) and the 2007 Bengkulu-Mentawai earthquake ($M_w$ 8.6), which both produced much higher PGA values, typically exceeding 0.1 g. This difference is due to the greater magnitude and closer proximity of those events compared to the scenario used in this study. Therefore, the findings of this research can be regarded as a lower-bound estimate.

Table 2. PGA analysis results and amplification factor values

| Site | PGA Input (g) | PGA Surface (g) | Amplification Factor |
|---|---|---|---|
| GM-1 | 0.0012 | 0.0005 | 2.3962 |
| GM-2 | 0.0027 | 0.0009 | 3.1467 |
| GM-3 | 0.0008 | 0.0005 | 1.5768 |
| GM-4 | 0.0002 | 0.0002 | 1.2021 |

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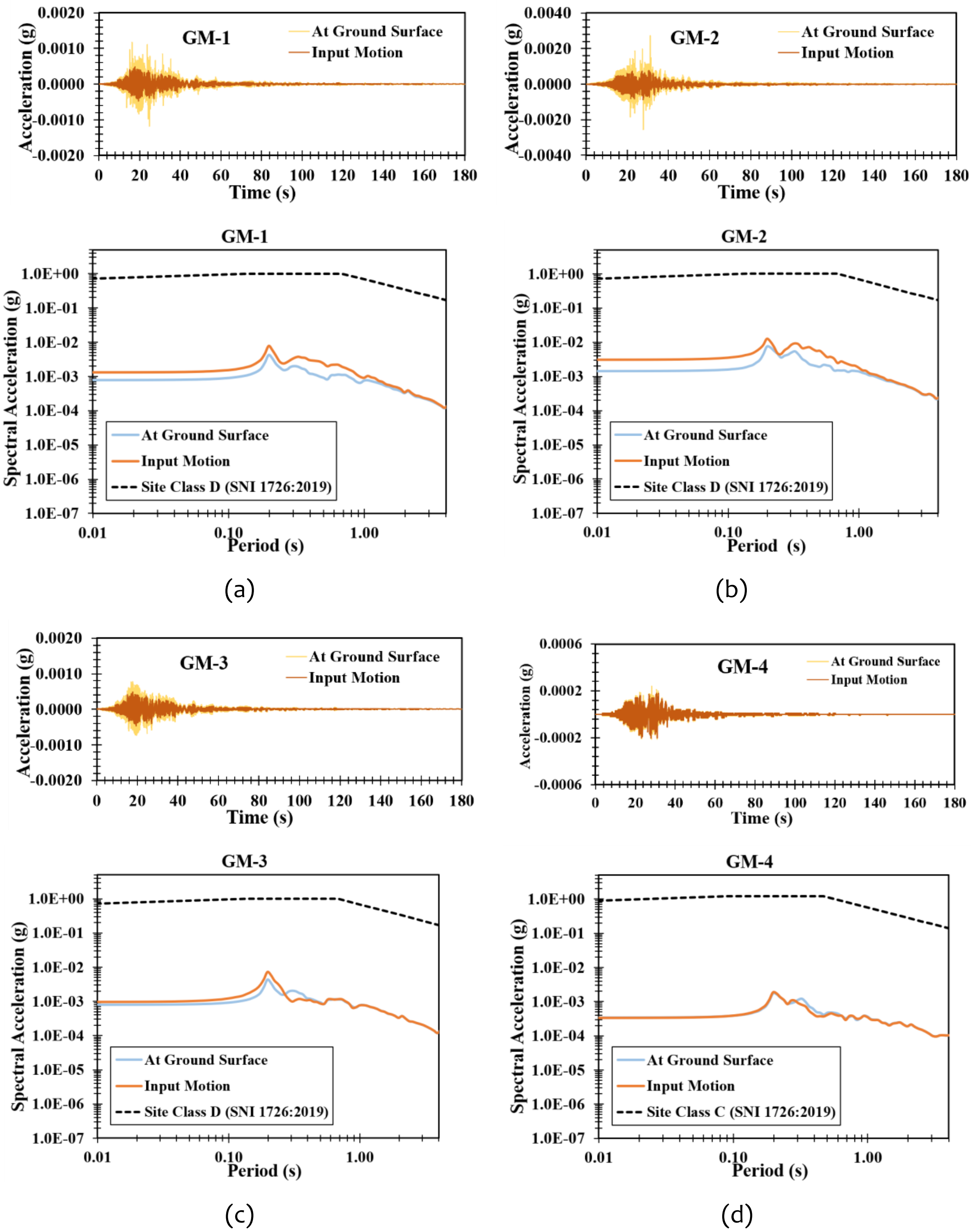


Figure 7. Results of the analysis comparing the spectral acceleration and the time history for (a) GM-1, (b) GM-2, (c) GM-3, and (d) GM-4

## CONCLUSION

This study examines the one-dimensional ground-seismic response in Bengkulu Province to a Mentawai earthquake scenario using a site-specific seismic response analysis approach. The findings demonstrate that local soil conditions, especially the $Vs_{30}$ parameter and soil stiffness, play a significant role in shaping the surface seismic response by causing variations in amplification and spectral response at each site. These results highlight that seismic response is affected not only by the characteristics of the earthquake source but also by local geological conditions and soil dynamic properties, which govern the propagation and amplification of seismic waves. Therefore, conducting site-specific seismic response analysis is essential for enhancing earthquake hazard assessments and informing the planning of earthquake-resistant infrastructure in Bengkulu Province.

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