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Evaluation of Stilt Houses in Lebong Regency Against Earthquakes, Incorporating Ground Response and Structural Dynamics Analysis

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ABSTRACT

Lebong Regency, located in Bengkulu Province, Indonesia, is in an earthquake-prone zone due to its proximity to the Ketahun Segment, part of an active fault system in the region. This condition makes the area highly vulnerable to seismic activity. The purpose of this research is to analyze the performance of stilt houses in Lebong Regency using an integrated methodology comprising ground response analysis and structural dynamics analysis to assess the potential effects of earthquakes. Site characterisation was undertaken to generate geological data in the area of study, marking the first stage of the study. The analysis proceeded with ground-shaking analysis to determine the characteristics of ground motion, including critical parameters such as the maximum ground acceleration (PGA), spectral response acceleration, and amplification factors. The next step was to simulate the propagation of earthquake waves to determine the structural behavior of buildings under earthquake shocks. The analysis results show that the stilt houses will have sufficient structural resistance under earthquake loading before and after the earthquake. All wooden structural components satisfy design requirements and strength checks as per the relevant design requirements.

Keywords: *Earthquake; Ground Response; Stilt Houses; Structural Dynamics Analysis.*

1. Introduction

Bengkulu Province is one of Indonesia's regions highly vulnerable to earthquakes. This vulnerability is caused by three primary sources of seismic activity in the surrounding area: the Sumatera Subduction Zone, the Mentawai Fault, and the Sumatera Fault. The three sources do cause major earthquakes, especially in the coastal and mountain regions of Sumatra Island [1]. One of the largest earthquakes ever recorded was the Bengkulu-Mentawai earthquake in 2007, with a magnitude of Mw 8.6, which caused widespread damage and served as an essential reference for the design of earthquake-resistant structures in western Indonesia [2], [3]. Previous studies have also noted that Bengkulu experiences high seismic intensity, which is the level of ground shaking felt during an earthquake that can cause severe structural damage and pose a significant threat to public safety [4].

One of Bengkulu's provinces, including Lebong Regency, is classified as having a high or very high seismic vulnerability index [5]. Its proximity to the earthquake source makes the area highly susceptible to direct impacts from major earthquakes [6]. Amidst these risks, many buildings, especially reinforced concrete structures, show weaknesses in withstanding significant earthquake loads [7]. In this context, a building's performance is strongly influenced by earthquake type, construction materials, and site conditions. Therefore, using seismic design codes is crucial in ensuring the safety and suitability of building structures.

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One approach used to assess the performance of structures against earthquakes is seismic response analysis through the finite element method (FEM) based numerical modelling [8]. This approach will reflect the complex interplay between the structure and the ground on which it is placed and thereby deliver a more realistic view of a building's dynamic behavior. Ground surface vibrations in spectral form were simulated in this study using the FEM method, following the one-dimensional seismic response simulation [9]. Nonlinear dynamic analysis simulations will utilize the seat-by-seat ground motion records elected so that their effectiveness can be evaluated on buildings [10], [11]. Nonlinear dynamic analysis enables the structural response to be modelled more realistically in response to earthquake time history inputs, encompassing aspects such as ductility and soil–structure interaction. The nonlinear time history method is considered more appropriate for lightweight timber structures with highly dynamic characteristics. Research has also demonstrated that this approach can better represent the actual seismic response of timber connections and the overall structural performance [12]. Seismic data from the research location is an essential basis for evaluating the capacity of buildings against earthquake loads [13]. In this procedure, a one-dimensional forward model is applied to a soil layer, and the resulting parameters include peak ground acceleration (PGA), spectral response acceleration, amplification factors, and time history information. These data are required to examine the structure's overall dynamic behavior.

Lebong Regency is also known for its traditional stilt houses, most of which are constructed using wood. Several examples of these stilt houses are shown in Figure 1. Given the high seismic potential in this area, it is crucial to understand the extent to which stilt house structures can withstand seismic loads. Assessing the performance of these structures is vital not only for ensuring comfort but also for occupant safety. The lack of studies discussing the resistance of wooden structures in Lebong Regency, particularly stilt houses, highlights the need for more in-depth research. Thus, the focus of this study is to test the performance of stilt houses during earthquakes by integrating ground response and structural dynamics into the analysis. In such a way, it is possible to study the ground motion in an arrangement and stir it into the framework, and thus, receive a better picture of the weaker elements of the building and their reaction to the general seismic charge. It will therefore be suggested that the findings of this research will support disaster risk management and earthquake-resistant structures in potential zones such as the Lebong Regency.

Figure 1. Stilt Houses in Lebong Regency

2. Material and Method

2.1. Study Area

The study took place in Lebong Regency, Bengkulu Province, with two data collection points located in Amen Subdistrict (LB-1) and Pelabai Subdistrict (LB-2), as shown in Figure 2. These have been chosen as areas where they lie close to the Ketahun Segment of the active Sumatera Fault System and where several stilt houses are in the vicinity. Lebong Regency itself is geologically part of the Sumatera Fault Zone, a strike-slip dextral deformation zone that stretches south to north across the Sumatera island. The central system, consisting of a few of its parts that cut across the Bengkulu Province, is referred to as the Ketahun Segment [14]. Recent research by [15] revealed that the

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Ketahun Segment has the potential to generate seismic activity capable of causing structural damage. This segment is found in the mainland of Lebong Regency and can be deemed to be one of the main earthquake sources in the area. Figure 2 shows the location of this segment, while Figure 3 displays a three-dimensional model of the stilt house structure under study in Lebong Regency.

In general, Lebong Regency has varied geological conditions, consisting of several rock formations, including Andesite Basalt Volcanic Rocks, Rhyo Andesite Volcanic Rocks, the Bal Formation, Hulusimpang Formation, Seblat Formation, Granite, Seblat Granite, Granodiorite, Langkup Granodiorite, and the Maur Formation. These geological conditions are illustrated in Figure 2, which depicts the research location and the overall geological characteristics of Lebong Regency.

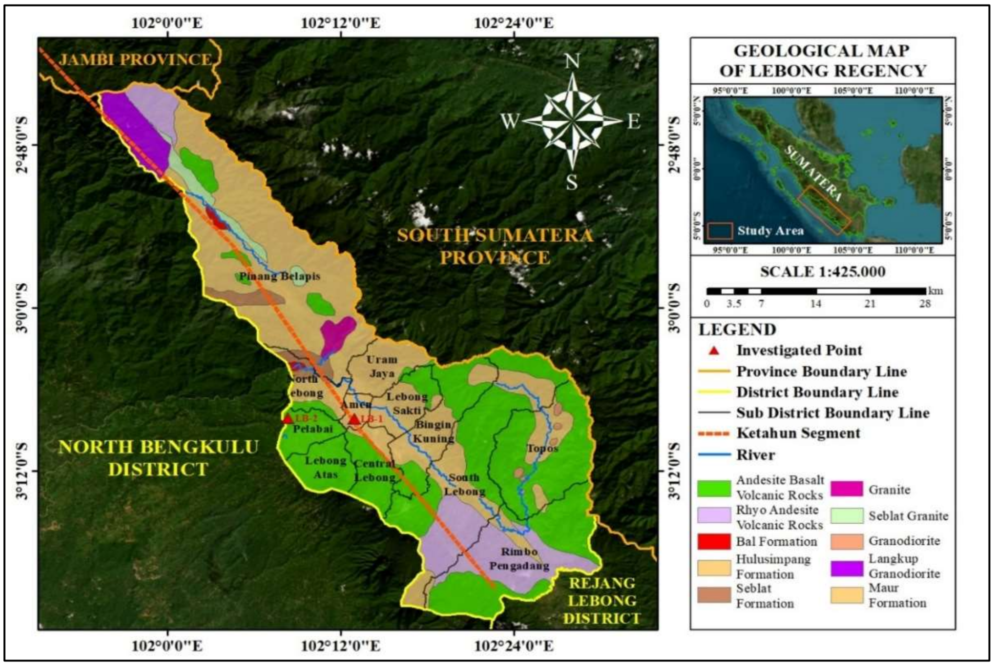

Figure 2. The regional geological map of Lebong Regency, and investigated points

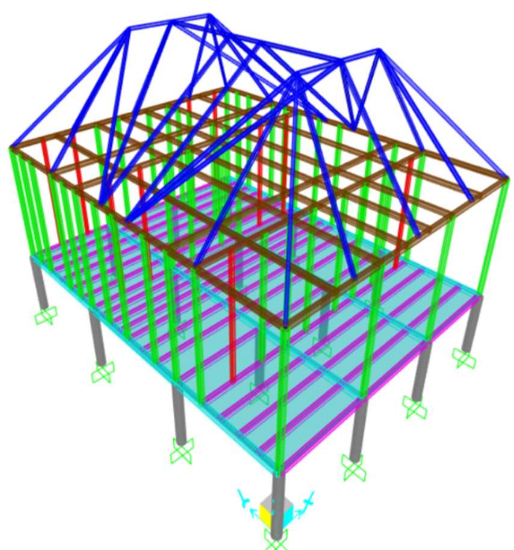

Figure 3. Research building modelling

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2.2. Research Framework

This study was conducted in Lebong Regency, Bengkulu Province, to integrate seismic ground response analysis and structural dynamics analysis. The research process began with field data collection and calculations of soil parameters to understand the geotechnical characteristics of the study site. This analysis used historical data from several major earthquakes, namely the Bengkulu–Mentawai Earthquake (Mw 8.6, 2007), the Kobe Earthquake (Mw 6.9, 1995), and the Coyote Earthquake (Mw 5.7, 1979). Based on the bedrock surface, ground motion was modelled and transmitted to the ground surface through the soil horizons above the bedrock. The technique is critical for calculating the ground's behaviour during a large earthquake and for predicting how it would affect the building on top of the soil. Earthquake records in this study were analysed using a one-dimensional non-linear analysis to determine the impact of earthquake wave propagation on soil and structural behaviour. Peak Ground Acceleration (PGA) data were used to assess structural performance in accordance with applicable seismic design standards [16]. Earthquake waves are transmitted from the bedrock to the surface through each soil layer, producing a time history of ground motion which is then analysed [17]. The time history is then employed in structural dynamic analysis, in which parameters, such as the PGA and spectral acceleration, are cross-fielded as earthquake inputs into the appropriate building structure model. Once all the geometrical aspects of the building are modelled, the next step is to determine the structural loading: load cases, load combinations, and the origins of the masses. The results are verified by a time history analysis, which measures the structure's behavior, especially the distribution of stress ratios, visualised as a colour gradient on the structure. Additionally, internal forces such as normal forces (N), shear forces (V), and bending moments (M) are calculated to identify potential weak points in the structure. Shear forces are particularly critical in structural design to prevent failure due to lateral forces during earthquakes.

2.3. Data Collection

The data in this study were obtained through field surveys, which included identifying the components of stilt houses, measuring shear wave velocity (V_s), and collecting ground motion history. The results of this research are likely to help civil engineers understand how the spatial variations in the properties of the ground moderate the effects on the geotechnical analysis, especially by modelling parameters like shear wave velocity (V_s) and unit weight of soil (γ). Seismic tests in the subsurface were conducted to obtain shear-wave velocity data for each soil layer [18]. In general, the primary material used for stilt houses in Lebong Regency is balam wood, which belongs to strength class II, with a density of 670 kg/m³ and an elastic modulus (E) of 100000 kg/cm². Table 1 summarises the structural components of the stilt houses analysed.

Table 1. Structural Element Data

Structure Element	Dimension (cm)
Building Length	890
Building Width	690
Height of Ground Floor	168
Roof Height	275
Pedestal Column Diameter	20
Column 1	9 × 9
Column 2	7 × 7
Beam 1	12 × 12
Beam 2	10 ×10
Ring Beam	7,5 × 10
Roof Truss	5 × 7

Figure 4 presents geotechnical data from the research location, including essential parameters such as shear wave velocity (V_s) and unit weight of soil (γ). Soil density is used to determine soil physical properties, while V_s is a key parameter in seismic analysis and geotechnical engineering.

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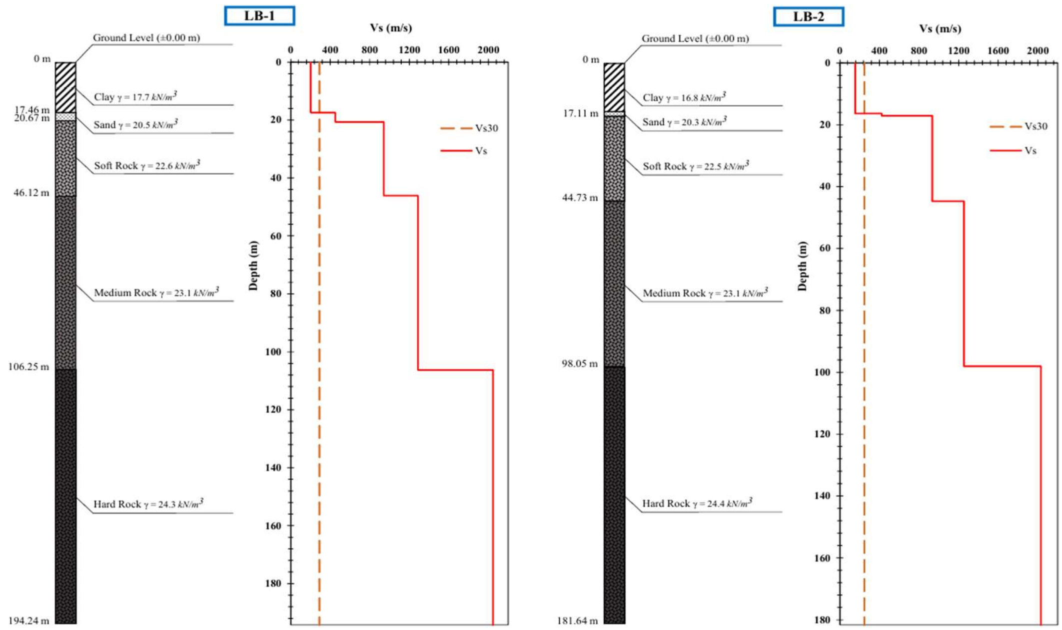
The higher the V_s value, the greater the soil stiffness, indicating that the soil is denser and more complex. In this context, V_{s30}, the average shear wave velocity to a depth of 30 metres from the ground surface, is used as a general indicator in seismic site classification. According to research [19], [20], Vs values vary across layers, with soft soils tending to have lower Vs values, while hard soils tend to have higher V_s values. This is because spatial variations in geotechnical parameters, including soil unit weight (γ), are a critical aspect in the determination of the response to a seismic event and the stability of a structure. This is reinforced by research [21], which found that natural soil properties tend to vary spatially. Ignoring these variations can lead to errors in risk estimation and result in inaccurate or unsafe structural designs.



(a) (b)

Figure 4. Site investigation data for the study location, (a) LB-1, (b) LB-2

2.4. Combined Method of Ground Response and Structural Dynamics Analysis

The analysis of building performance under dynamic conditions, such as during an earthquake, is quite essential to ensure the safety and resilience of structures. Seismic vibrations that travel between the bedrock and the ground surface can, at the right time, influence the stability of buildings. So, the interaction between these waves and the ground and structures during seismic events is vital to understand in civil engineering design. The seismic response of the ground has been addressed through a nonlinear one-dimensional analysis, and the time-history analysis is considered in this study. Various essential parameters, such as peak ground acceleration (PGA), spectral response acceleration, and others. They were used to obtain a realistic view of how the ground behaves in resonance with the vibrations of earthquakes. Outcomes such as time histories of ground motion and spectral acceleration provide detailed data on the nature of the earthquake response in the ground. Seismic wave propagation modelling was performed to calculate parameters such as PGA and the amplification factor (AF) using a pressure-dependent hyperbolic model. Of these parameters, PGA is the central measure, as it quantifies the maximum acceleration a ground surface experiences during an earthquake, which is very important for determining the repercussions that could result from a specific seismic event [22]. Site response analysis was conducted to evaluate the ground behaviour as seismic waves propagate from the bedrock to the surface through horizontal soil layers. Earthquake inputs were selected based on the geological conditions and specific characteristics of the study site, ensuring that the analysis results better reflect field conditions.

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The Finite Element Method (FEM) is a numerical modelling technique used to understand the response of structures to dynamic loads. Three-dimensional FEM modelling enables a more detailed analysis of the dynamic interaction among building structures, foundations, and the supporting ground. By integrating ground parameters obtained from seismic response analysis and time history data, FEM can simulate the behaviour of structures during an earthquake. This approach provides a more comprehensive understanding of how structures respond to seismic loads and how the surrounding geotechnical environment affects structural behaviour. The combination of seismic response analysis and FEM modelling provides valuable information for evaluating the performance of structures in real-world earthquakes. The findings of such techniquess not only aid the development of safer zones, but also further our understanding of complex situations between their bases and the frameworks amid tremors [3].

2.5. Ground Motion Parameter

The input parameters for the analysis are seismic waves, which generate critical parameters such as peak ground acceleration (PGA). Among the parameters that can be obtained from this analysis is the amplification factor, which explains how much more the ground accelerates as waves travel from the bedrock to the surface. This increase is due to differences in material properties, particularly the shear wave velocity (Vs), between hard bedrock and softer sedimentary layers. Generally, the V_s velocity decreases with increasing depth, reflecting softer, less dense ground conditions. Research [23] indicates that, with increasing depth, shear wave velocity increases.

The one-dimensional seismic response analysis computes the amplification factor (AF) as the ratio of the maximum acceleration at the ground surface (PGAsurface) to the acceleration at the bottom of the structure or the input layer (PGA_{input}) [24]. This comparison determines the extent of acceleration increase due to local ground characteristics. The amplification factor can be obtained through the following Equation 1:

$$AF_{\max} = \frac{PGA_{surface}}{PGA_{input}} \tag{1}$$

3. Result and Discussion

3.1. PGA (Peak Ground Acceleration) Profile

Analysis of seismic response using hyperbolic models yields essential parameters, including peak ground acceleration (PGA), spectral response acceleration, and amplification factors. PGA is the highest acceleration when seismic waves move from the bedrock to the surface of the rooted ground. The parameter is critical in determining a given area's susceptibility to earthquakes, since the higher the PGA, the greater the damage that may occur. Additionally, PGA can reflect local seismic conditions and is used to understand earthquake characteristics, including subduction earthquakes, making it highly beneficial for structural damage mitigation efforts [6].

Figures 5 and 6 present the PGA profiles from the seismic response analysis results at two locations. At point LB-1 (Amen Subdistrict), the highest PGA value was recorded at 0.674 g on the surface layer due to the Kobe earthquake. This layer is dominated by clay material, which significantly amplifies ground motion during large earthquakes. This study examined five ground layers, with PGA values of 0.570 g, 0.052 g, 0.042 g, and 0.373 g for the second to fifth layers, respectively. The differences between these layers are relatively small, again showing clay's dominant role in amplifying vibrations. At point LB-2 (Pelabai Subdistrict), similar results were obtained. The highest PGA value was found in the surface layer at 0.583 g due to the Kobe earthquake waves. The clay-dominated material in this layer was again proven to have high amplification potential. The PGA values in the second to fifth layers were 0.546 g, 0.504 g, 0.493 g, and 0.426 g, respectively. The amplification factor (AF) obtained from the analysis at this location was approximately 1.121, slightly higher than the value at LB-1 (1.070).

The differences in PGA values and amplification factors between the two locations are closely related to variations in shear wave velocity (V_s) between layers. The lower the V_s velocity in the surface layer, the higher the amplification factor. This means that soft and less compact soil layers

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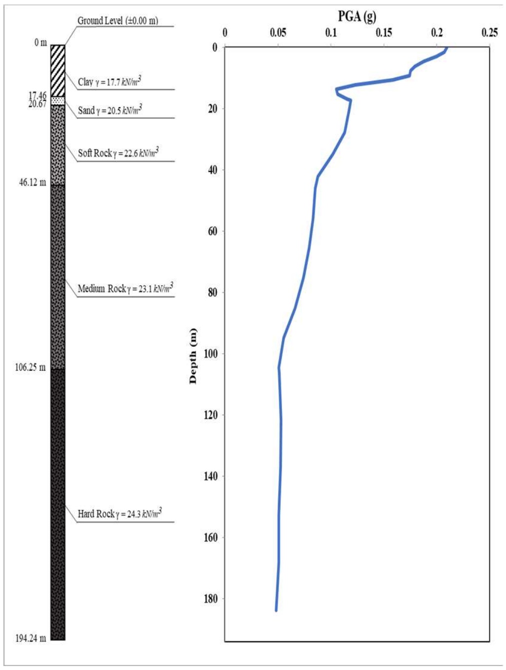
tend to amplify earthquake vibrations more. This is in line with the findings of research [25], which stated that the amplification factor is greatly influenced by wave propagation velocity, where lower velocities result in higher amplification, reflecting lower rock density and strength.



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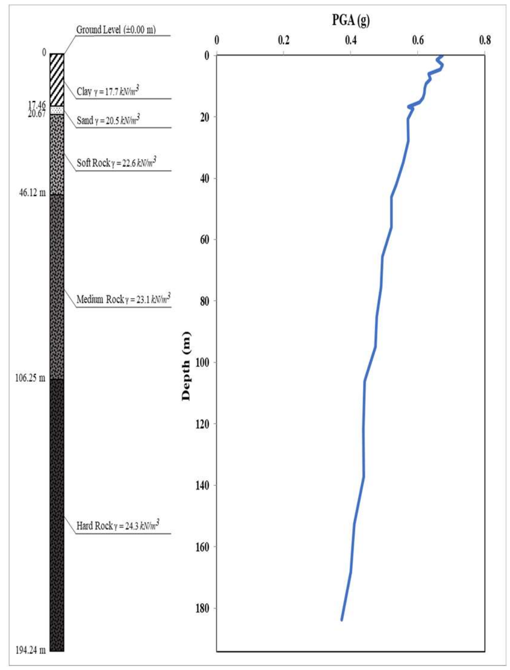

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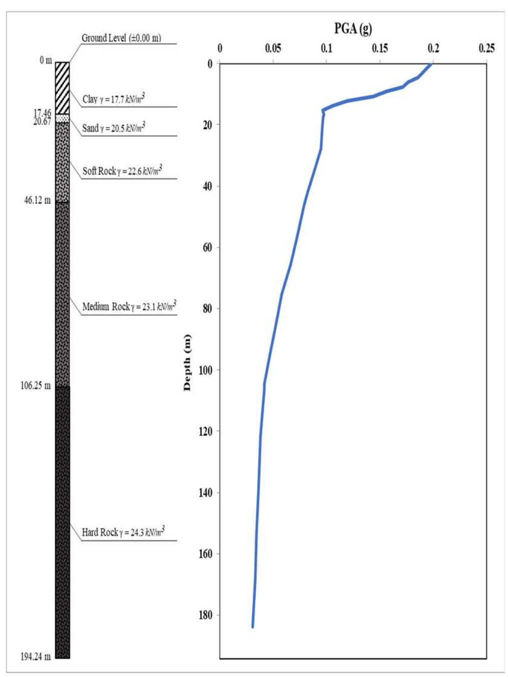

(c)

Figure 5. Profile of peak ground acceleration (PGA) at point LB-1, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote

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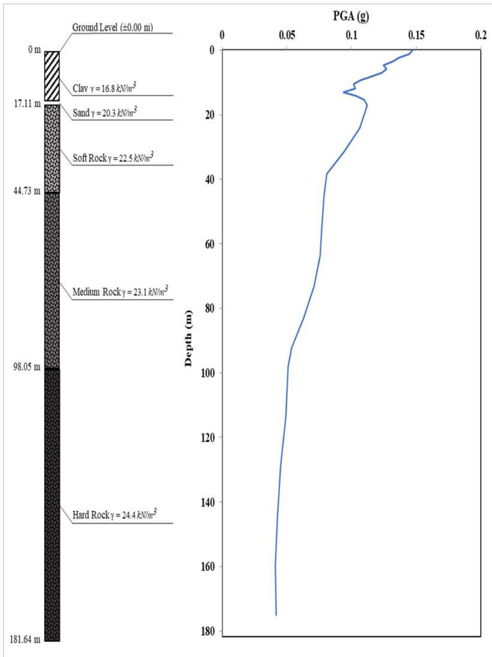

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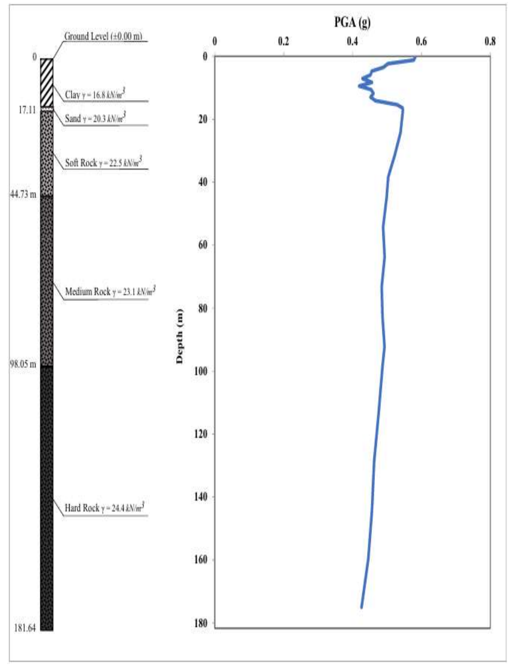

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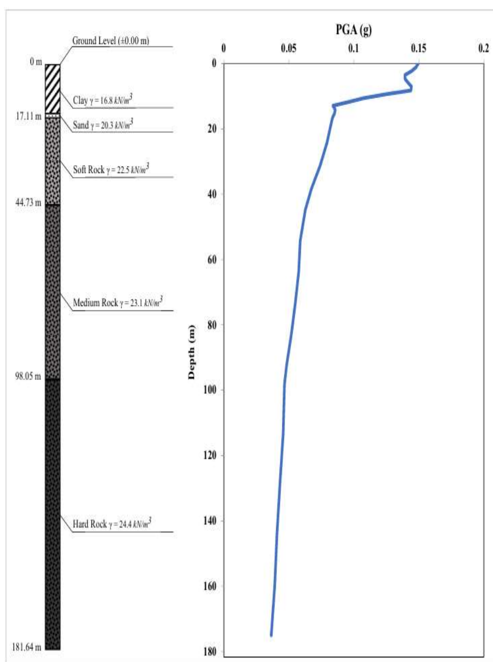

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Figure 6. Profile of peak ground acceleration (PGA) at point LB-2, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote

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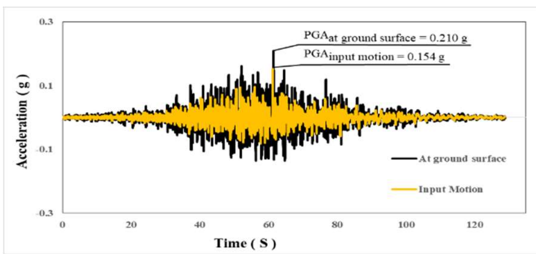
3.2. Time History of Ground Motion

The history of acceleration on the ground surface and earthquake input motion are presented in Figures 7 and 8, respectively. Based on the analysis results at point LB-1, the peak ground acceleration (PGA) was 0.674 g, while at point LB-2 it was 0.603 g. These two values indicate that the greatest probable acceleration occurred in the surface layer due to the transmission of seismic waves during the Kobe earthquake. The acceleration time history also shows that the peak acceleration in the input motion does not match the ground-level acceleration [26].

The ground motion simulated in the present study can be considered a reflection of the effects of the most powerful major earthquakes in the study area. It is used as a basis for predicting how building structures will respond during an earthquake. In line with the findings of research [27], the short dominant period of these seismic motions indicates the potential for significant impacts on low- to medium-rise buildings. Short-period motions tend to generate larger inertial forces in structures with high natural frequencies, thereby increasing the risk of damage to buildings with low to medium heights.



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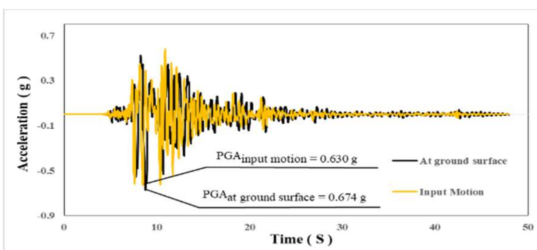

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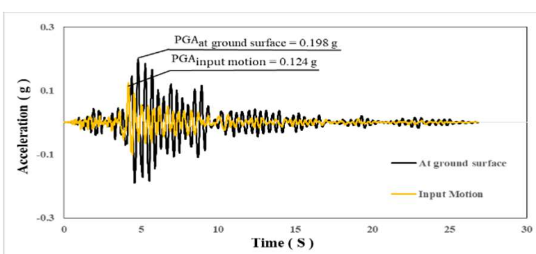

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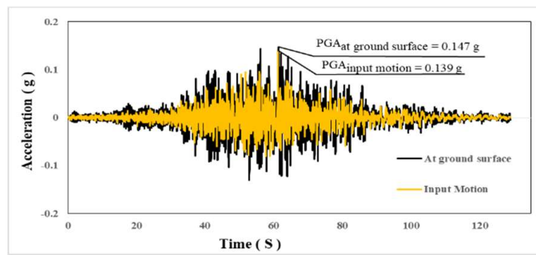
Figure 7. Time history of ground motions at point LB-1, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote



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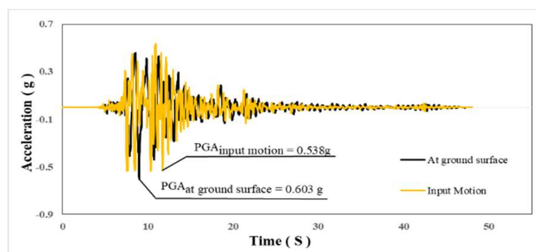

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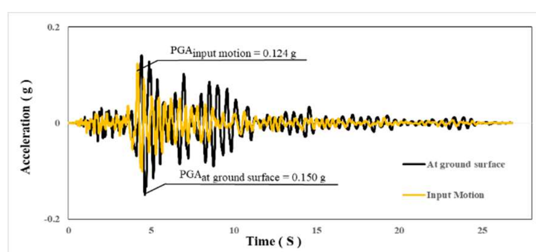

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Figure 8. Time history of ground motions at point LB-2, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote

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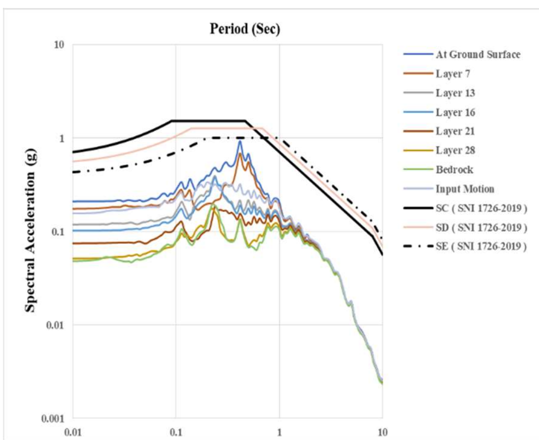
3.3. Spectral Acceleration

Figures 9 and 10 present graphical representations of spectral response acceleration. Based on the seismic response analysis of the ground, the peak spectral acceleration was found to occur at the ground surface layer. The results of this study reveal that the spectral acceleration values recorded at the surface exceeded those predicted by seismic response modelling of the location. Similar findings were also reported by research [28] in their study in Banten Province, where the spectral acceleration at the motion input was smaller than at the ground surface, with the result that seismic motion was amplified as the waves traversed the structure upwards.

The spectral acceleration curve for the surface layer was obtained by evaluating ground motion from earthquakes, including the analysed acceleration time history. Based on these results, it can be concluded that the stilt houses in Lebong Regency generally meet the applicable structural design requirements and exhibit relatively safe performance under earthquake shocks. It is only necessary to note that the spectrum-based acceleration at the ground side is likely to have a reading that is more than the design spectral acceleration, at the medium range period. This is a prerequisite for structural plans, since the spectral acceleration values measured at ground level in some cases reach levels equivalent to those required by the national earthquake design codes, namely SNI 1726:2012 and SNI 1726:2019, which serve as the primary references for the planning of earthquake-resistant buildings and non-buildings in Indonesia.



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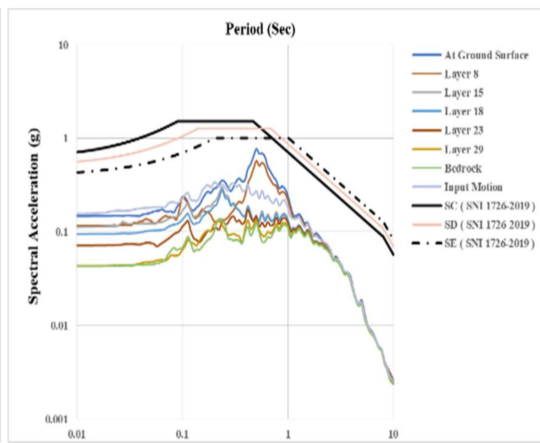

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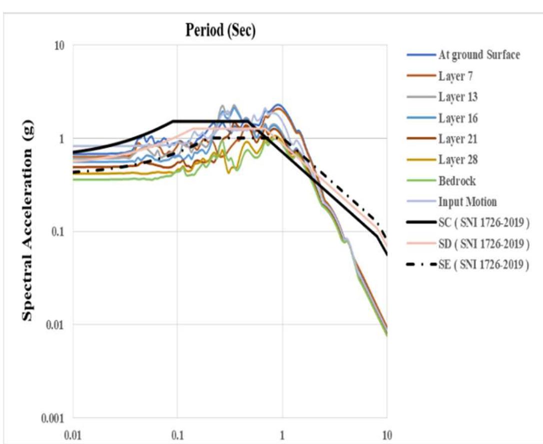

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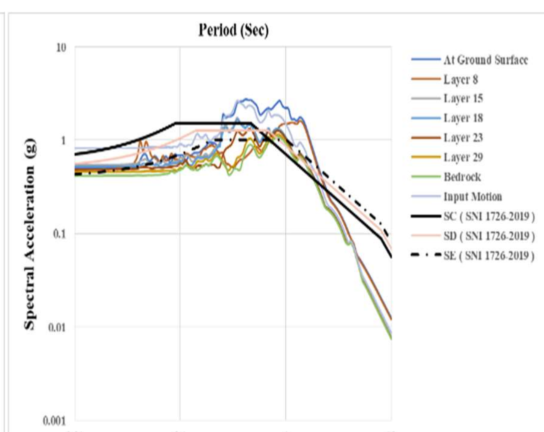

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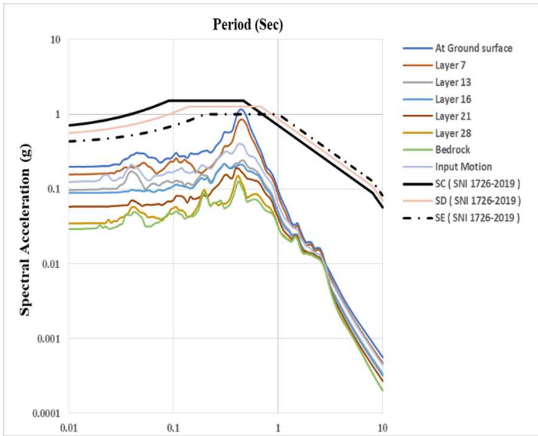

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Figure 9. Spectral acceleration comparison at point LB-1, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote

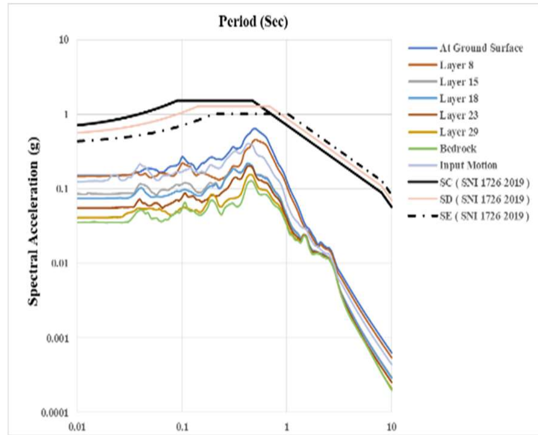

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Figure 10. Spectral acceleration comparison at point LB-2, (a) Bengkulu-Mentawai, (b) Kobe, (c) Coyote

3.4. Dynamic Response of the Building

Finite element modelling is used to analyse a building's response to various types of loads, including permanent loads, time-varying loads, and earthquake-induced pressures. Following the modelling and structural analysis, the building's performance under earthquake loading is evaluated through mass participation in the vibration modes. This mass participation indicates the extent to which the building's mass participates in a particular vibration pattern, defined by the building's mode shapes under dynamic loading.

The results of the finite element analysis are used to determine the forces in the structure. Table 2 shows the maximum forces in the structure before an earthquake. Recorded regular forces are between 0.130 kN and 0.354 kN, shear forces between 0.004 kN and 0.150 kN, and the maximum bending moment between 0.012 kNm and 0.147 kNm.

The seismic response analysis follows seismic loading on the future structure to demonstrate a considerable rise in the values of internal forces at point LB-1. According to Table 3, the ranges of the normal force are 0.167 kN-2.374 kN; the range of the shear force is 0.008 kN-1.046 kN; and the maximum range of moment is 0.029 kNm-4.290 kNm. An identical trend is also encountered at point LB- 2, as presented in Table 4, where the normal force measures between 0.107 kN and 2.012 kN; shear force between 0.005 kN and 0.295 kN; and maximum bending moments between 0.018 kNm and 3.403 kNm.

Comparing the values of the internal forces before and after the earthquake loading reveals differences. This suggests that the earthquake acceleration applied to the structure influences the magnitude of the internal forces generated. In general, internal force values increase after the structure is subjected to earthquake loads, although in some cases moments or shear forces may decrease, depending on the structure's response and the earthquake's properties. Moment reduction may occur in flexible structures that can effectively dissipate earthquake energy, thereby reducing the forces transmitted to structural elements. Conversely, rigid structures tend to be unable to absorb energy effectively, leading to increased moments and greater potential for damage.

Based on the overall evaluation results, the analysed stilt houses demonstrated good structural performance before and after being subjected to earthquake loads. All wooden structural elements passed the design inspection and met the required strength standards. This design evaluation is essential at every stage, from initial planning, the construction process to the operational phase of the building. This aligns with the findings of research [29], which concluded that traditional wooden houses in West Sumatera have adequate resistance to internal forces generated by seismic activity.

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Table 2. Assessment of structural forces before seismic loading

Structure Element	Normal Force (kN)	Shear Force (kN)	Moment (kNm)
Pedestal Column	0.226	0.063	0.147
Column 1	0.354	0.015	0.048
Column 2	0.058	0.004	0.012
Beam 1	0.081	0.009	0.137
Beam 2	0.116	0.004	0.012
Ring Beam	0.130	0.105	0.130
Roof Truss	0.277	0.011	0.015

Table 3. Assessment of structural forces after seismic loading at point LB-1

Structure Element	Maximum Element Strength								
	Mentawai			Kobe			Coyote		
	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)
Pedestal Column	1.106	0.198	1.342	2.374	0.458	4.290	1.249	0.196	1.650
Column 1	0.899	0.041	0.367	1.816	0.102	0.773	0.959	0.043	0.387
Column 2	0.493	0.008	0.144	1.042	0.021	0.301	0.511	0.008	0.158
Beam 1	0.167	0.417	0.280	0.432	1.046	0.592	0.187	0.503	0.305
Beam 2	0.277	0.035	0.228	0.652	0.083	0.545	0.327	0.040	0.249
Ring Beam	0.238	0.178	0.321	0.544	0.380	0.685	0.256	0.189	0.353
Roof Truss	0.514	0.025	0.029	1.103	0.053	0.060	0.547	0.026	0.032

Table 4. Assessment of structural forces after seismic loading at point LB-2

Structure Element	Maximum Element Strength								
	Mentawai			Kobe			Coyote		
	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)	Normal Force (kN)	Shear Force (kN)	Moment (kNm)
Pedestal Column	0.712	0.108	0.970	2.012	0.295	3.403	0.739	0.112	1.174
Column 1	0.554	0.023	0.221	1.547	0.065	0.630	0.575	0.024	0.229
Column 2	0.303	0.005	0.089	0.856	0.013	0.252	0.305	0.005	0.092
Beam 1	0.107	0.279	0.174	0.383	0.897	0.497	0.127	0.315	0.178
Beam 2	0.183	0.021	0.142	0.555	0.069	0.435	0.198	0.024	0.161
Ring Beam	0.151	0.107	0.201	0.418	0.310	0.582	0.164	0.118	0.210
Roof Truss	0.313	0.013	0.018	0.892	0.041	0.052	0.340	0.014	0.019

4. Conclusion

Based on research on stilt houses in Lebong Regency that combined ground response and structural dynamics analyses during an earthquake, data on earthquake acceleration history and amplification factors were obtained, which are very important for evaluating soil-structure interaction. Dynamic site analysis showed that the dominant soil layer was clay, with the spectral acceleration results still within the safe limits specified by the national seismic design standards (SNI 1726:2019). This suggests that stilt houses designed in accordance with seismic design standards have adequate resistance to earthquake loads and are safe from significant structural damage. For further research, a more in-depth analysis is recommended, particularly of soil layer characterisation. This can be achieved by increasing the number of geotechnical data collection points and using more diverse subsurface investigation methods. Such data will become more accurate in illustrating the ground conditions at the research site and enhancing the quality of seismic response analysis and soil–structure interaction. In addition, socio-economic considerations, such as the practicality and affordability of design improvements within the local community context, should be evaluated to ensure the recommendations can be implemented in practice. Furthermore, future studies should

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assess seismic performance using broader structural parameters, such as ductility, collapse mechanisms, drift capacity, and P–delta curves, to provide a more comprehensive evaluation of structural resilience.

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