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Unveiling Differences in Seismic Response: Comparative Study of Equivalent Linear and Nonlinear Analyses in the Central Coastal Region of Bengkulu, Indonesia

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ABSTRACT Seismic response analysis is a key aspect in earthquake geotechnical engineering, as it provides important insights into the behavior of soils when exposed to seismic forces. This research compares equivalent linear and non-linear models in the central coastal region of Bengkulu, which is known for its complex geology and high seismicity. By evaluating the accuracy and reliability of each model in predicting ground motion amplification, this research aims to provide useful recommendations for seismic design. The research method uses one-dimensional equivalent linear and nonlinear propagation modeling, namely Pressure Dependent Hyperbolic (PDH). The analysis resulted in the parameters of Peak Ground Acceleration (PGA), time history acceleration, spectral response acceleration, and amplification factor. The equivalent linear method consistently produced higher values for peak ground acceleration (PGA), spectral response acceleration, time history acceleration, and amplification factor compared to the nonlinear method. The analysis results show that the equivalent linear PGA values are in the range of 0.32g to 0.63g, while the nonlinear values range from 0.20g to 0.52g. The resulting spectral responses are averaged over the design spectrum within 0.2s to 0.9s, which can affect low- to high-ceilinged buildings. The equivalent linear amplification factor has a range of 1.59 to 1.91, while the nonlinear has a range of 0.80 to 1.59. Both methods have their advantages, with the nonlinear approach offering greater accuracy for large seismic events, while the equivalent linear model remains useful for preliminary analysis. Hopefully, these findings will improve the understanding of ground response in coastal areas and provide valuable data for improving infrastructure resilience in earthquake-prone areas around the world.

KEYWORDS Earthquake, Peak Ground Acceleration, Spectral Acceleration, Time History Acceleration, Amplification Factor

1 INTRODUCTION

Seismic response analysis of soil is fundamental to geotechnical earthquake engineering, as it provides critical insights into how soil behaves under seismic forces. Understanding the soil's response is crucial for designing infrastructure that can endure earthquake-induced stresses. Earthquake-induced ground motions significantly affect the performance of buildings, bridges, and other essential structures, making it imperative to conduct detailed seismic response analyses. In many instances, soil amplifies seismic waves, which can lead to greater ground shaking at the surface than at the bedrock level (Civelekler et al., 2024). This amplifying effect depends on factors like soil type, density, and thickness, all of which must be considered during seismic design (Ozmen, 2023). According to Molua and Ataman (2021), soil-structure interaction can lead to variations in seismic response across different sites, which is why site-specific analyses are often necessary. Moreover, considering the significant loss of life and property associated with seismic events, such as the 2004 Indian Ocean earthquake, the need for precise soil response prediction has grown considerably (Saatcioglu et al., 2005). Seismic response analysis is thus a key tool in mitigating earthquake risks and ensuring safer designs, particularly in regions with high seismic activity.

A fundamental method for predicting seismic effects is the acceleration response spectrum, which indicates how different frequencies of seismic waves affect the movement of the ground and structures. This spectrum is used to estimate the likely response of buildings and other infrastructure to varying earthquake magnitudes. Seismologists and engineers use it to design structures that can accommodate the predicted range of frequencies, minimizing the risk of catastrophic failure. Ground motion recordings from past earthquakes, like the Northridge (1994) and Kobe (1995) earthquakes, have contributed significantly to the development of these spectra (Mohraz and Sadek, 2001). These records help in understanding how earthquake magnitude influences the frequency content and amplitude of seismic waves as they travel through different geological layers. Studies, such as that by Mase (2018*a*), have shown that acceleration response spectra vary considerably based on the soil profile and depth to bedrock. In coastal regions with soft sediments, such as those in Bengkulu, the response spectra can be particularly pronounced, highlighting the importance of localized response analysis for infrastructure safety.

To represent the complex behavior of soils during seismic events, one widely adopted approach is the equivalent linear model, which accounts for soil nonlinearity in a simplified manner. This model adjusts the stiffness and damping properties of soil based on strain levels, allowing engineers to estimate how soil will respond under moderate seismic shaking (Bakhtaoui, 2024). While computationally efficient, the equivalent linear model operates on the assumption that soils exhibit linear behavior at each level of strain, with properties modified iteratively to simulate nonlinearity. This simplification makes it popular for large-scale seismic response analyses, particularly in the early stages of design (Bakhtaoui, 2024). Guyader and Iwan (2006) pioneered the development of the equivalent linear model, which has since been applied in numerous studies, including those for major infrastructure projects. However, its effectiveness is often limited to scenarios with small to moderate earthquakes, as it does not fully capture the large strains and permanent deformations that occur during stronger seismic events (Nguyen et al., 2018). Nonetheless, it remains a valuable tool for preliminary evaluations, especially when used alongside more detailed methods.

In contrast, non-linear models provide a more accurate and detailed representation of soil behavior, particularly during strong ground shaking. These models account for the true stress-strain relationship of soils, enabling a more comprehensive analysis of soil responses during seismic events. Unlike the equivalent linear model, non-linear models do not rely on assumptions of modified linear behavior but instead simulate how soils respond to cyclic loading, capturing the effects of strain softening, hysteretic damping, and permanent deformations (Dai et al., 2024). The development of non-linear models has been instrumental in cases where significant soil-structure interaction is expected, or when designing for large seismic events. For instance, the work by Qodri et al. (2021) on nonlinear behavior in seismic response analysis provided a framework for accurately modeling large deformations in soil layers. Misliniyati et al. (2019) have carried out a seismic response validation study from a simulated ground model to represent vertical records during a strong earthquake in an effort to determine the most optimal earthquake wave propagation model. The main findings of this study indicate that nonlinear models are more suitable for describing earthquakes with high acceleration rates. Recent applications, such as those used in earthquake-prone areas like Japan and California, have demonstrated that non-linear models offer superior accuracy in predicting ground motions, though they require considerably more computational resources (Yan and Zhang, 2023). For critical structures, like nuclear power plants or high-rise buildings, non-linear analyses are often essential to ensure structural safety.

Given the strengths and weaknesses of both equivalent linear and non-linear models, it is important to compare these approaches to determine which is more suitable under various seismic conditions. Equivalent linear models, though less computationally demanding, may not capture the full extent of soil behavior during large earthquakes, particularly when soils experience significant strain (Adampira et al., 2015; Yan and Zhang, 2023). Non-linear models, on the other hand, offer greater accuracy but at the cost of increased complexity and computational time (Yan and Zhang, 2023). Comparative studies, such as those by Civelekler et al. (2024); Mir Mohammad Hosseini and Asadollahi Pajouh (2012) have shown that for certain soils, equivalent linear models can underestimate ground motion, leading to potentially unsafe design conclusions. However, non-linear models may overestimate soil responses in cases where nonlinearity is less pronounced (Yan and Zhang, 2023). Therefore, conducting a comparative analysis is essential for understanding when each model should be applied. This comparison is particularly important for regions where soil conditions and seismic activity create unique challenges for engineers.

Bengkulu's central coastal region presents a valuable case study for comparing the performance of these two models. Located along the western coast of Sumatra, the region is close to the highly active Sumatra fault line and the Sunda Megathrust, making it highly susceptible to strong earthquakes and tsunamis. Historically, the province has experienced a number of earthquakes, including two significant ones: a Mw 7.9 earthquake in 2000 and a Mw 8.6 earthquake in 2007. These earthquakes were the largest recorded in the region, causing substantial damage to public infrastructure and resulting in a significant number of casualties. The soil conditions in this region vary, with soft sediments near the coast and stiffer soil inland, complicating the prediction of seismic responses (Mase, 2018*a*). Previous studies in the region, such as those by Mase (2018*b*), have shown that ground motion amplification in coastal Bengkulu can be significant due to the presence of weak soil layers. The use of both equivalent linear and non-linear models in this region can provide insights into how each approach predicts seismic responses under real-world conditions. This case study can highlight the advantages and limitations of each model, offering practical guidance for engineers working in similar coastal environments.

Despite the growing body of research on seismic re-

Figure 1 Seismotectonic Conditions in Bengkulu Province and The Investigated Location

sponse models, there remains a knowledge gap regarding their application in regions with complex geological conditions, such as Bengkulu's central coast. Most studies have focused on either equivalent linear or nonlinear models independently, without thoroughly comparing their performance in regions with layered soils and high seismicity. This study aims to bridge that gap by conducting a detailed comparison of the two models in the Bengkulu coastal region. The primary objectives are to evaluate the accuracy and reliability of each model in predicting ground motion amplification and to provide recommendations for their use in seismic design. The results of this study will not only contribute to the understanding of soil response in coastal regions but will also provide valuable data for improving infrastructure resilience in other seismically active areas worldwide.

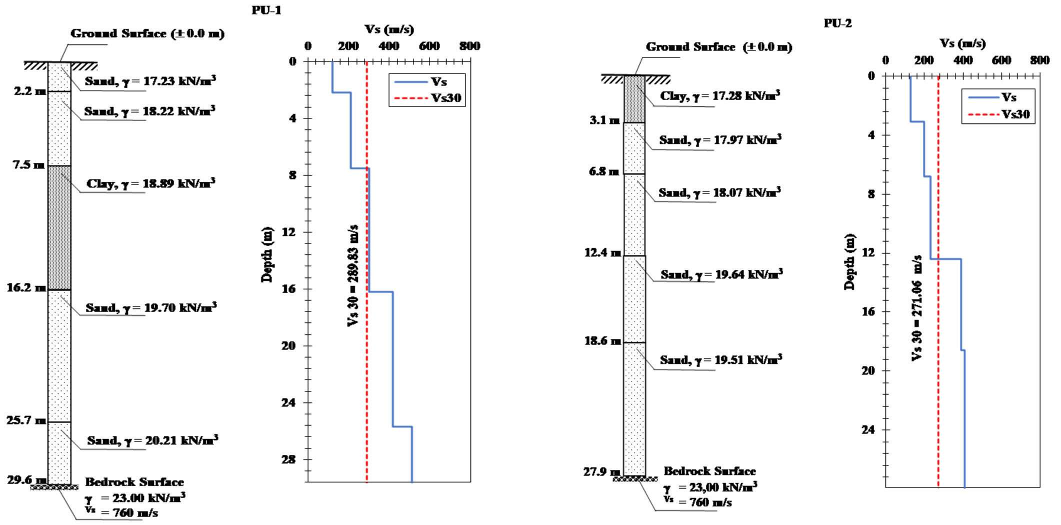
2 METHODS

2.1 Study Site and Soil Layers

This study was conducted in the coastal areas of Central and North Bengkulu Regencies in Indonesia and the seismotectonic conditions of these regions are influenced by the Sumatran Fault, Mentawai Fault, and Sumatra Subduction Zone Figure 1, making it one of Indonesia's most earthquake-prone areas. These fault systems can trigger seismic activity, and the region's proximity to earthquake epicentres heighten the risk.

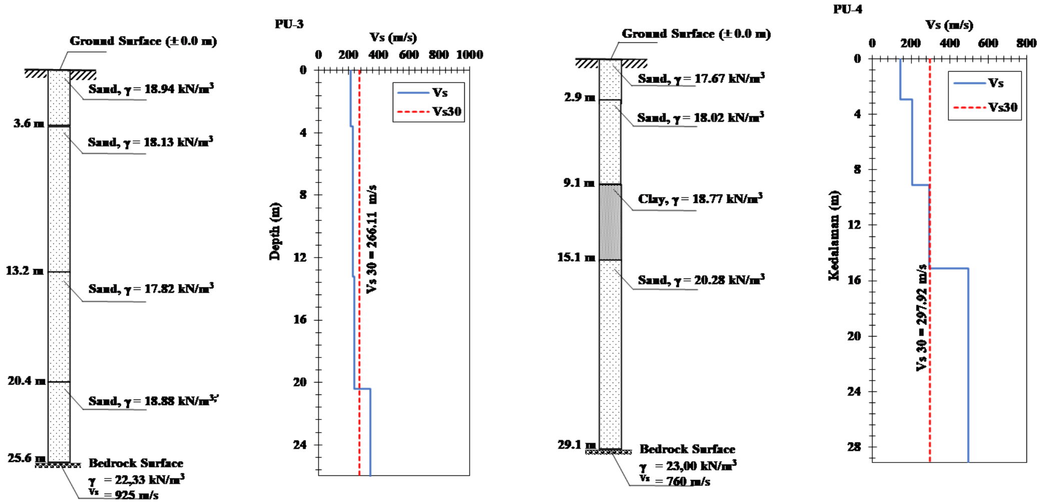
The area also consists of coastal plains bordered by hills with varied slopes, primarily made up of Tertiary sedimentary rocks, mountain debris, and Quaternary deposits from beaches, rivers, and swamps. Many Tertiary rocks have undergone weathering, resulting in soft, unconsolidated materials that, together with loose Quaternary sediments, amplify earthquake shocks. Additionally, in the steeper hilly areas, weathered rocks are susceptible to landslides, which can be triggered by strong seismic activity, further compounding the earthquake risk in the region. Despite these seismotectonic settings, the regions undergo significant spatial development as a hub for tourism, residential, governmental, commercial, and metropolitan activities.

The research points are symbolized by PU-1 to PU-6 representing their respective regencies. PU-1 to PU-3 are in North Bengkulu Regency and PU-4 to PU-6 are in Central Bengkulu Regency. To characterize soils in the study site, six shear wave velocity tests were performed, with 3 in North Bengkulu (PU-1 to 3), whereas 3 others in Central Bengkulu Regency (PU-4 to 6). According to the results of this investigation (Figure 2), the study site is dominated by sand, as it is located in



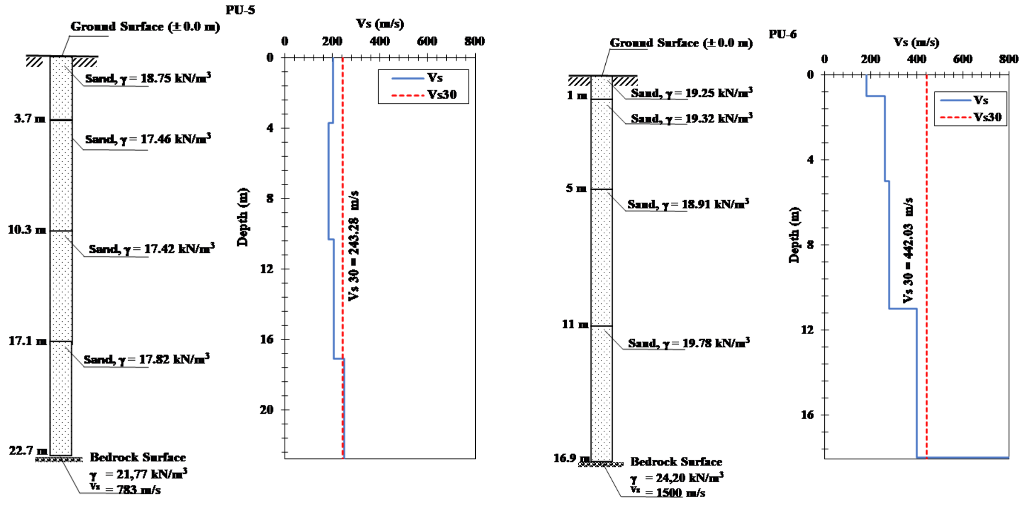
(a) PU-1

(b) PU-2



(c) PU-3

(d) PU-4



(e) PU-5

(f) PU-6

Figure 2 Seismotectonic Site Investigation Result.

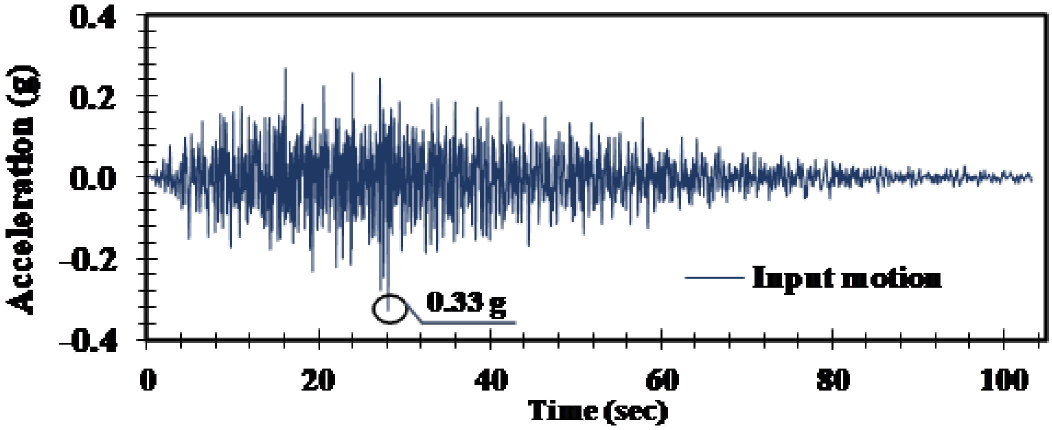
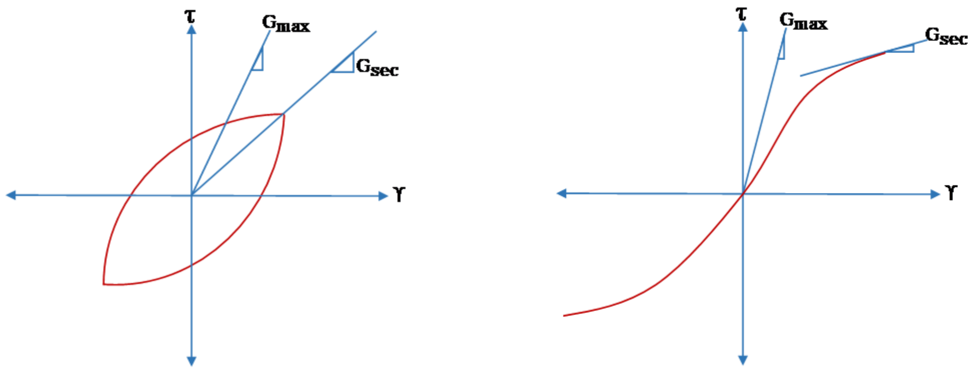


Figure 3 Scaled Input Motion (Mase, 2017).



(a) Equivalent Linear

(b) Nonlinear

Figure 4 Shear Modulus Estimation Curve.

the coastal area. The 30 m depth time-average shear wave velocity (V_{s30}) of the study site ranged between 243.28 m/s-442.03 m/s, with PU-6 showed the highest (V_{s30} = 442.03 m/s), whereas PU-5 (V_{s30} = 243.28 m/s) showed the lowest. V_{s30} can be determined based on the following equation.

$$V_{s30} = \frac{30}{\sum \frac{h_i}{V_{si}}} \tag{1}$$

where, hi is the thickness of the calculated layer and V_{si} for shear wave velocity for the calculated layer.

Hence, PU-1 to PU-5 with V_{s30} values ranged between 243.28 m/s to 297.92 m/s were classified as medium soil (SD) according to the National Earthquake Hazard Reduction Program (NEHRP). On the other hand, PU-6 with V_{s30} = 442.03 m/s was categorized as hard soil (SC).

2.2 Seismic Wave Modelling

We applied one-dimensional PDH (Pressure-Dependent Hyperbolic) wave propagation to model vertical shear wave propagation in soil layers (Hashash, 2016) and examined the soil response to cyclic loading (Hashash and Park, 2001). This method is able to capture the actual behavior of the soil, especially in situations where the pressure and load conditions vary, such as in seismic events and cyclic loading. During the cyclic loading, soil stiffness was altered, changing soil shear modulus, and causing the soil to behave inelastically (Hashash, 2016). To simulate these conditions, we used the scaled 2007 Bengkulu-Mentawai earthquake wave developed by Mase (2017), as shown in Figure 3. This input wave, with a PGA value of 0.33g, was applied to analyze both equivalent linear and nonlinear wave propagation using the PDH model.

The equivalent linear model approximates nonlinear shear stress–shear strain behavior by using an equivalent shear modulus, calculated as G_{sec} (Figure 4). However, in reality, the relationship between shear stress and shear strain is not truly linear. This discrepancy highlights the need for models that can more accurately represent soil behavior under dynamic or cyclic loading, which is inherently nonlinear. In response, the nonlinear model was developed, using the true nonlinear shear strain–shear stress relationship, based on the hyperbolic backbone curve and employing G_{tan}. The equivalent linear method simplifies nonlinear soil

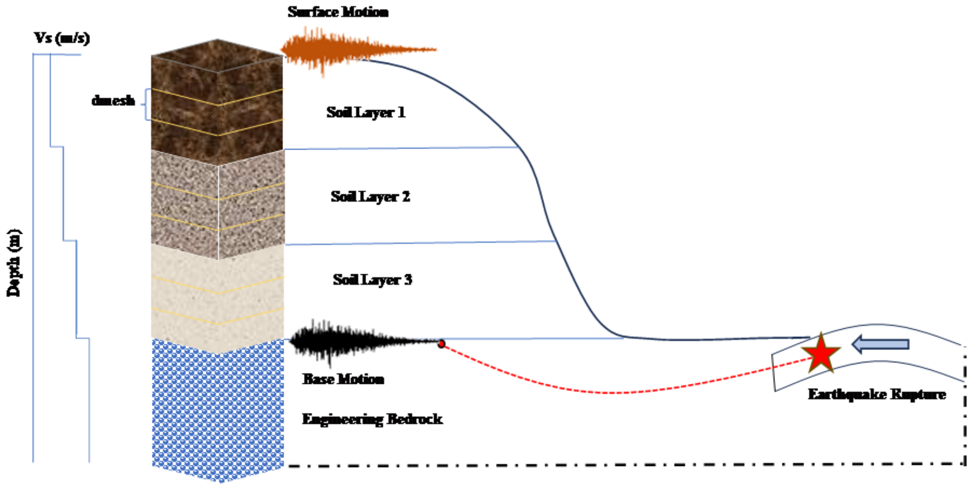


Figure 5 Wave Propagation Scheme.

behavior by using an equivalent shear modulus (G) and an equivalent linear damping ratio (ξ) to represent the nonlinear hysteresis of soil during seismic events.

2.3 Data Analysis

Seismic waves are propagated from the bedrock to the ground surface (Figure 5), where their behavior is analyzed. Earthquake-generated waves, such as P-waves and S-waves, initially travel outward from the source through the bedrock, moving quickly due to the high seismic velocities of dense materials like granite. Upon reaching the interface between bedrock and overlying sediments, the waves undergo reflection and refraction—some energy reflects back, while the rest continues into the slower, less dense sediments, reducing wave speeds.

As these waves propagate through sediment layers, P-waves slow down, while S-waves may dissipate entirely if the material is unconsolidated or saturated with water. Near the surface, surface waves such as Rayleigh and Love waves are generated, causing ground shaking, which can be amplified in loose or soft soils. This shaking can significantly impact structures, depending on the intensity of the waves and the local geological conditions. To represent this process in the model, we used soil stratification data of the study site and the scaled 2007 Bengkulu-Mentawai earthquake wave (Mase, 2017) as the motion input.

According to Hashash (2016), each soil layer should have a minimum frequency of 30 Hz for accurate modeling. In this study, we used a mesh size of 0.5 m to 1 m, calculated by dividing the wave speed by four times the frequency, resulting in a frequency of 33 Hz. Therefore, the mesh derivative can be obtained by applying the assumptions listed in the following equation.

$$d = \frac{V_s}{4_f} \tag{2}$$

In Pressure Dependent Hyperbolic (PDH) analysis, the equations of motion and equilibrium of the system are defined in discrete time increments in the time domain on a lumped mass system. This lumped mass system is applied to a horizontally layered soil to solve the seismic response analysis problem. The application of the lumped mass system is carried out using Deepsoil software. The analysis began with the creation of a soil profile based on the soil properties of each layer. The soil profile is created by inputting all soil layer data including soil type, thickness of each soil layer (h), soil volume weight (γ_{sat}) and shear wave velocity (V_s). Next, dynamic parameters and plasticity index (PI) values are inputted. Dynamic parameters such as shear modulus $G/Gmax$ and damping ratio (ξ) are determined based on the soil type using reference curves. For granular soil the $G/Gmax$ curve of Seed and Idriss (1991), while cohesive soils use the $G/Gmax$ curve of Vucetic and Dobry (1991). Then, input the bedrock parameter data such as soil volume weight (γ_{sat}), shear wave velocity (V_s) and damping ratio (ξ). After that, Select the scaled 2007 Bengkulu-Mentawai earthquake wave motion input. Define minor strain damping by selecting a frequency-independent dumping matrix type. Frequency independence was chosen to reduce numerical dumping (Hashash, 2016). This analysis produces the parameters Peak Ground Acceleration (PGA), time history acceleration, response spectra acceleration, and amplification factor. After obtaining these values, the equivalent linear and nonlinear values are compared.

3 RESULT AND DISCUSSION

3.1 Peak Ground Acceleration (PGA)

Peak Ground Acceleration (PGA) produced by the equivalent linear method is different from that produced by the non-linear ones (Figure 6). In PU-1, PU-2 and PU-4, the PGA results are similar, showing 2–3 times higher PGA values at the loose and soft soil layers as compared to the bedrock layer. At all three points, the PGA values are relatively high, likely due to the presence of clay layers, which can amplify ground motion. During wave propagation, resonance phenomena occurred within certain layers, causing a significant increase in surface acceleration (Agustina et al., 2019).

In PU-3 and PU-5, the highest PGA values of 0.37g and 0.32g (mean: 0.375g) are observed at mid-depth rather than at the surface, which could be attributed to 27.60 m and 24.20 m thick sand layers that amplify the PGA. At PU-6, the PGA remains stable from bedrock to the surface. The greater bedrock depth is often associated with higher ground acceleration, as noted by Refrizon et al. (2013). Wibowo and Huda (2020) also observed that the impedance contrast between soft layers and bedrock affects the amplification factor. In general, seismic wave amplification occurs when waves move from a denser medium to a softer one.

The nonlinear PGA values of PU-1 to PU-6 are 0.20-0.52g, while the equivalent linear PGA is 0.32-0.63 g. Equivalent linear has a higher value compared to nonlinear. The study site is classified as an area with a very high earthquake risk (PGA: 0.3g to 0.4g), according to Fathani et al. (2008). Previous studies suggested that equivalent linear methods assume constant soil stiffness and damping during seismic loading, whereas real soils tend to soften and exhibit non-linear behavior under strong shaking, resulting in lower actual PGA values (Adampira et al., 2015). Yunita et al. (2015) in their research stated that the maximum surface acceleration value produced using an equivalent linear soil model exceeds a nonlinear soil model in various types of soil such as loose sand, dense sand, soft clay and stiff clay, for both short and long distance earthquakes. This was also stated by Finn et al. (1978); Yoshida (2015) which show that the shear stress passes the actual point on the stress-strain curve. thus, the maximum stress reaches an overestimate. The maximum overestimate occurs when the stress-strain curve is in a perfectly plastic state. The estimated shear stress also causes high acceleration above the existing layer.

3.2 Time History Acceleration

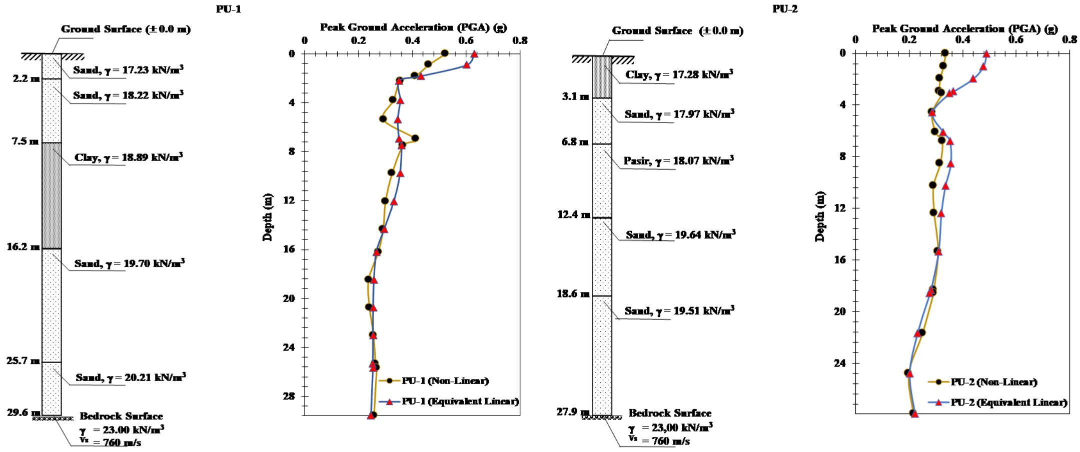
The time history acceleration was also different for the two methods, similar to the PGA (Figure 7). The nonlinear method generated acceleration within the range of 0.20g to 0.52g, whereas the linear equivalent method produced acceleration of 0.32g to 0.63g. The greatest time history acceleration value for the equivalent method was at PU-1 (acceleration: 0.63g), while the lowest was at PU-5 (acceleration: 0.32g). On the other hand, the highest time history acceleration value for nonlinear method occurred at PU-1 with acceleration of 0.52g, whereas the lowest was at PU-4 with 0.20g acceleration. Hence, we highlight that the linear equivalent approach tends to produce a higher maximum acceleration than that on the nonlinear approach. This phenomenon was associated with an overestimation of the shear stress by equivalent linear method, amplifying PGA value (Mase, 2018*a*). In addition, the influence of soft layers, which have relatively low resistance characteristics, causes an increase in the acceleration of earthquake waves approaching the surface, as these layers can amplify seismic waves by allowing for greater energy transfer and wave propagation effects (Jiang and Yang, 2024). Therefore, this study highlights the importance of site-specific seismic design or microzonation, as variations in soil conditions, such as soft layers, can amplify seismic waves and significantly impact the accuracy of acceleration predictions and building safety.

3.3 Spectral Response Acceleration

Analysis of equivalent linear and nonlinear seismic responses produces acceleration spectra with varying values for each period (Figure 8). A comparison of acceleration spectra from the analysis and design of SNI 1726:2019 acceleration spectra is presented. The analysis's equivalent linear and nonlinear spectral acceleration results tend to exceed the SNI 1726:2019 acceleration design. The equivalent linear spectral acceleration tends to be higher than nonlinear. The spectral acceleration value that passes design spectrum occurred at 0.2 to 0.9 s. According to the International Code Council (2017), this period range is included in the low to high building category. This shows that PU-1 to PU-6 sites is relatively unsafe when shaking due to an earthquake in both low and high-story buildings. This implies that the conventional seismic design approaches based on SNI 1726:2019 might underestimate the actual seismic forces, leading to potential structural vulnerability. Therefore, special attention and seismic design considerations are necessary for buildings within this site.

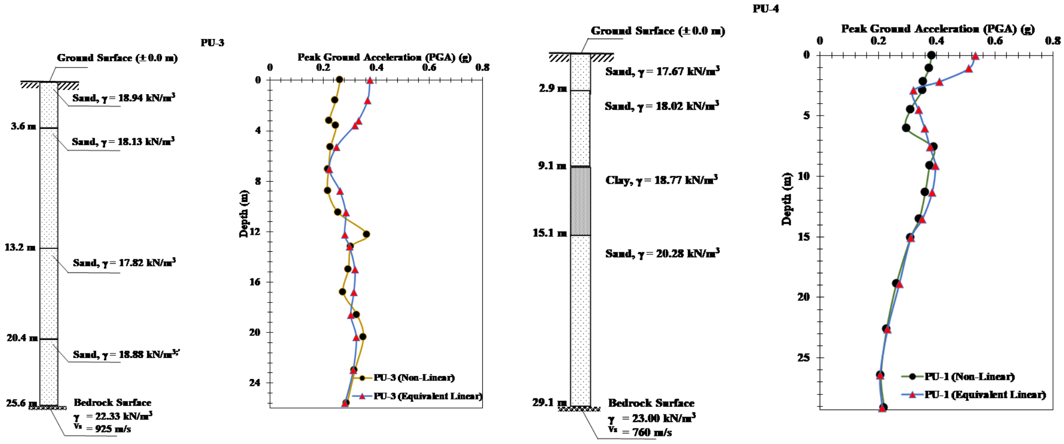
3.4 Amplification Factor

The amplification factor indicates the difference in magnification of earthquake acceleration from the bedrock to the ground surface. The variation of V_s in each soil layer causes this difference. The shear wave velocity (V_s) at the ground surface tends to be smaller



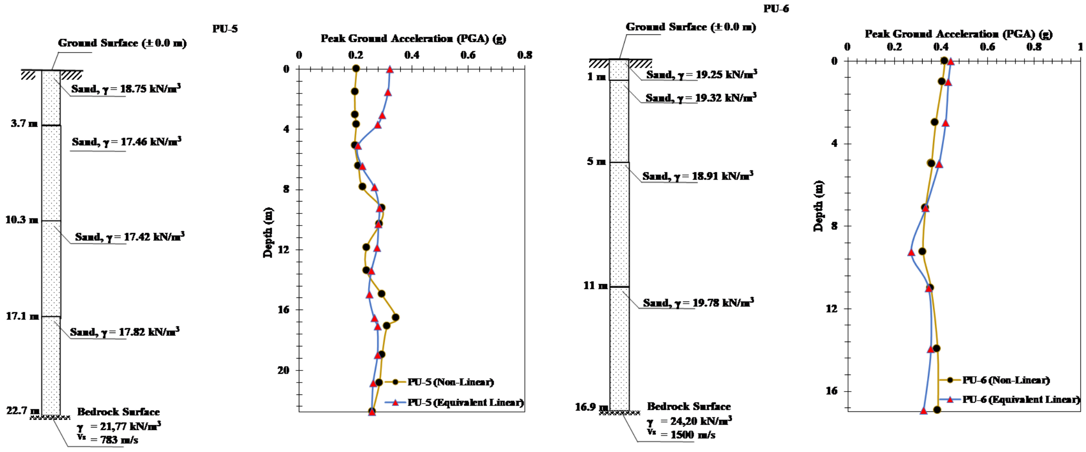
(a) PU-1

(b) PU-2



(c) PU-3

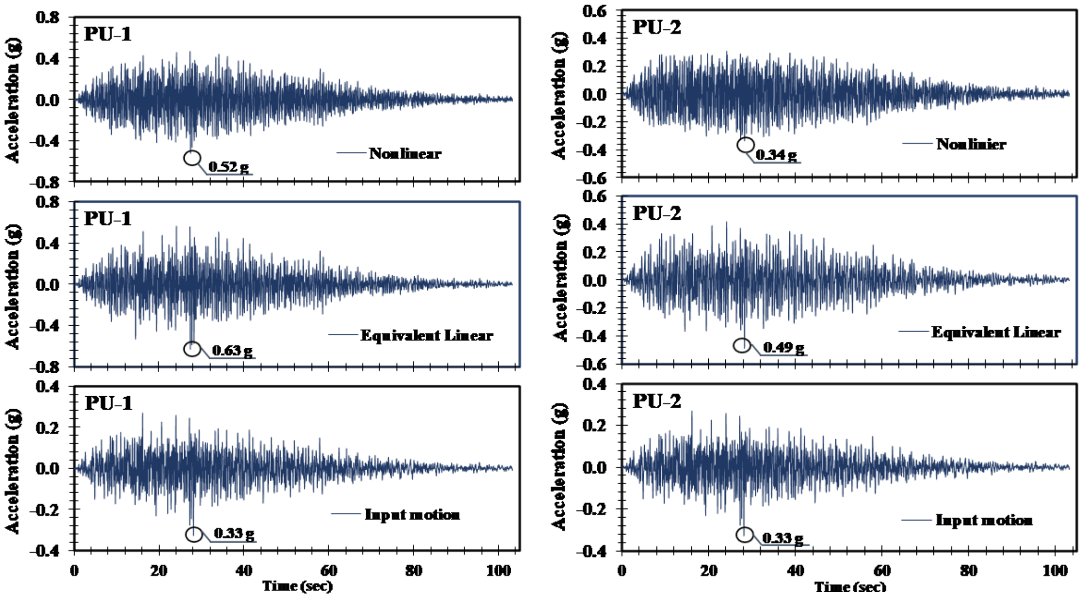
(d) PU-4



(e) PU-5

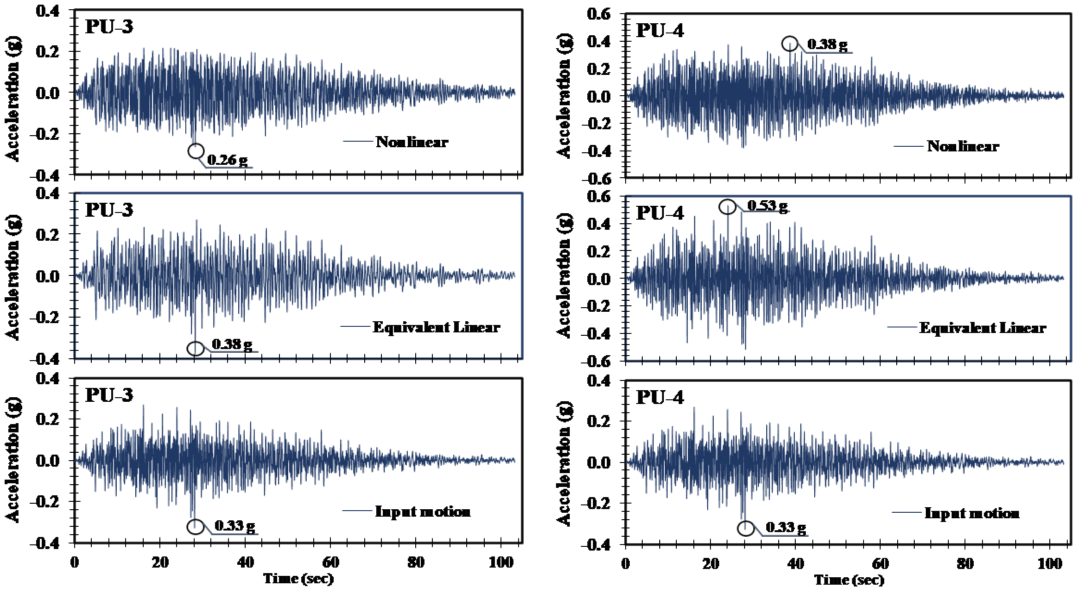
(f) PU-6

Figure 6 Peak Ground Acceleration (PGA) of Equivalent Linear and Nonlinear.



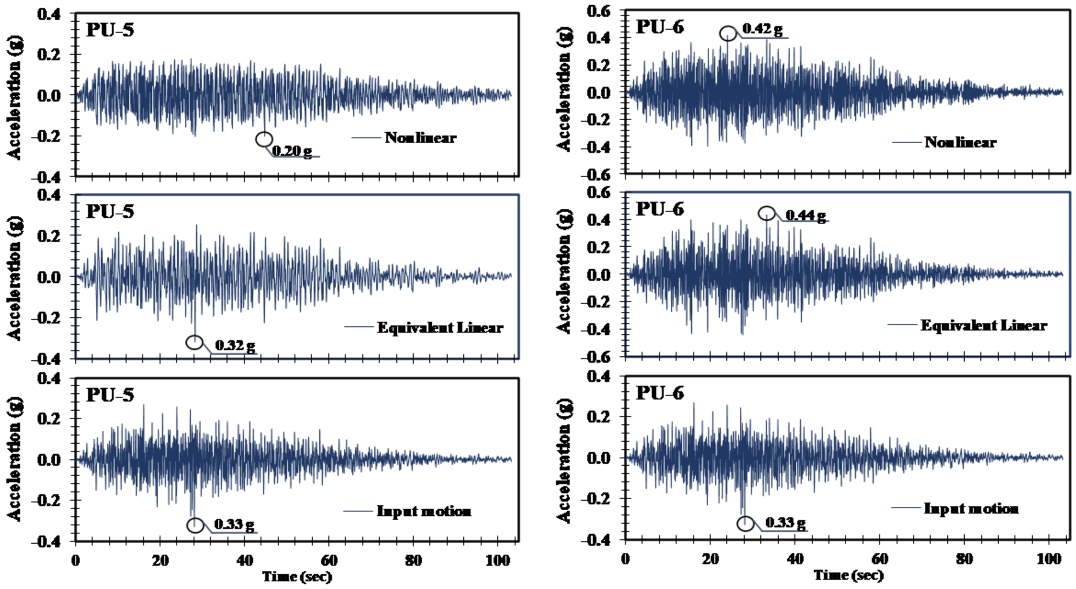
(a) PU-1

(b) PU-2



(c) PU-3

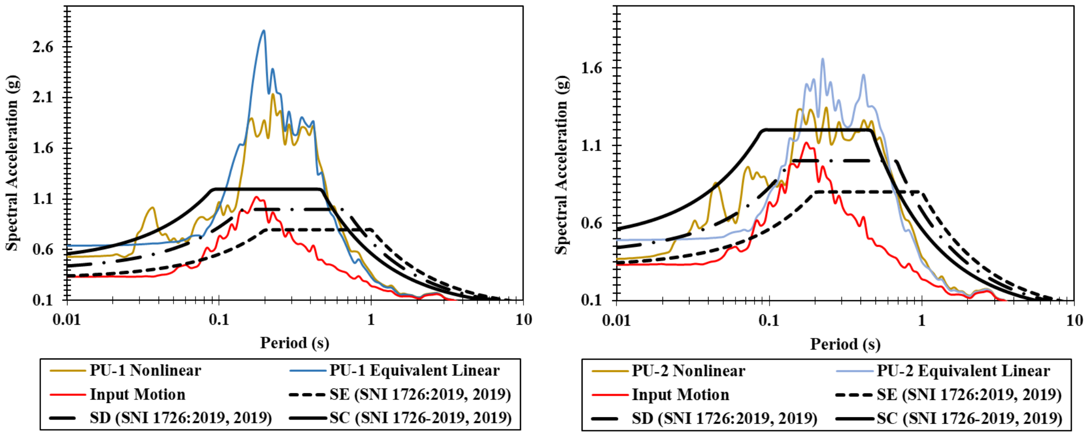
(d) PU-4



(e) PU-5

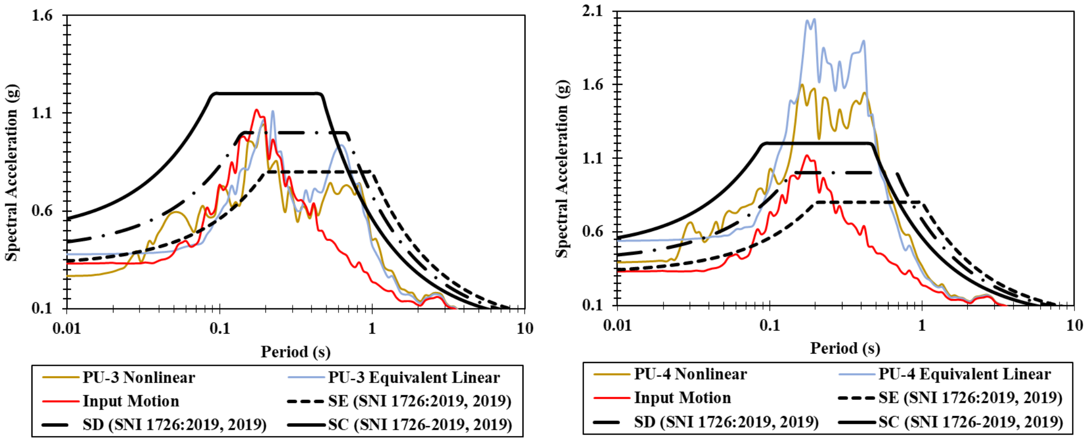
(f) PU-6

Figure 7 Time History Acceleration of Equivalent Linear, Nonlinear and Input Motion.



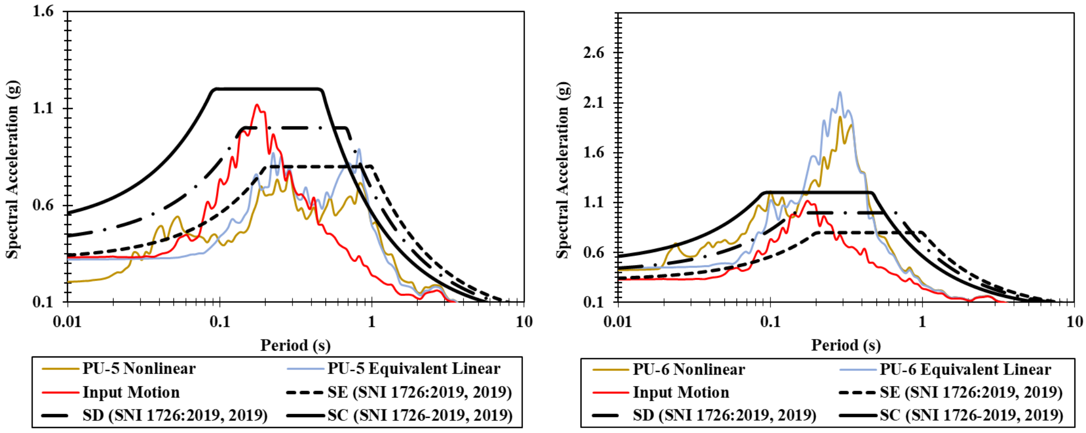
(a) PU-1

(b) PU-2



(c) PU-3

(d) PU-4



(e) PU-5

(f) PU-6

Figure 8 Spectral Acceleration.

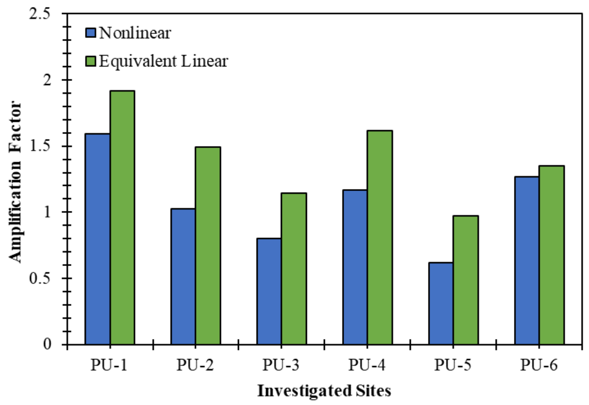


Figure 9 Comparison of Equivalent Linear and Nonlinear Amplification Factor.

than in the subsoil, resulting in a larger amplification factor. The amplification factor results from comparing the surface PGA value and the input motion. The graph of the PU-1 to PU-6 amplification factor values is shown in Figure 9 The nonlinear amplification factor value ranges from 0.80g to 1.59g, while the equivalent linear amplification factor ranges from 1.59g to 1.91g. The magnitude of an amplification factor could influence how fast the ground motion accelerates on the surface (Partono et al., 2013). Yoshida (2015) stated that the magnification of waves on the surface is influenced by the presence of a loose layer with a significant thickness, as found at points PU-1, PU-2 and PU-4. This area has a reasonably thick clay layer, potentially increasing the PGA value, especially in layers adjacent to the surface.

4 CONCLUSION

The comparison between equivalent linear and nonlinear seismic response analyses at PU-1 to PU-6 sites reveals important distinctions in how each method predicts seismic behavior, with significant implications for structural safety. The equivalent linear method consistently produces higher values for peak ground acceleration (PGA), spectral response acceleration, time history acceleration and amplification factor compared to the nonlinear method, suggesting that it may overestimate seismic forces due to its simplified assumptions about soil stiffness and damping. This overestimation aligns with previous research, which indicates that the linear equivalent method does not fully account for soil nonlinearity during strong shaking, resulting in higher acceleration predictions.

Moreover, the spectral response analysis indicates that both methods produce spectral acceleration values that exceed the design spectra outlined in SNI 1726:2019, particularly within the period range of 0.2 to 0.9 seconds. This period range is relevant for low to high-rise buildings, meaning structures on the PU-1 to PU-6 sites may face increased seismic risks. The findings underscore that conventional seismic design approaches might underestimate the true seismic forces, potentially leading to structural vulnerability.

Given these results, it is clear that site-specific seismic design and further investigations are critical, especially in areas with varying soil conditions like those observed in the Bengkulu coastal region. Both methods have their advantages, with the nonlinear approach offering greater accuracy for large seismic events, while the equivalent linear model remains useful for preliminary analysis. However, the need for careful seismic design in high-risk zones is emphasized, as the amplification of seismic waves through soft soil layers poses a considerable threat to infrastructure safety.

DISCLAIMER

The authors declare no conflict of interest.

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