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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 0.2 s to 0.9 s, 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

Bengkulu Province is located on the west coast of Sumatra Island. Seismotectonic conditions and geological conditions cause Bengkulu Province to become an area with high earthquake intensity in Indonesia. Bengkulu Province is located at the confluence of the Indo-Australian and Eurasian tectonic plates. The movement produced by the collision of the two plates creates active faults, namely the Sumatra Fault and the Mentawai Fault (Mase, 2021). This condition was the cause of a series of earthquakes and two large earthquakes throughout history that hit Bengkulu Province, namely an earthquake measuring 7.9 Mw in 2000 and an earthquake measuring 8.6 Mw in 2007. This earthquake was the largest earthquake that caused many losses. The earthquake caused damage to public facilities and claimed lives (Mase, 2018*a*).

The research focuses on the area on the Central Coast of Bengkulu Province. The Central Coastal area in question is Central Bengkulu and North Bengkulu Regencies. The Central Coastal Area of Bengkulu Province is an area that is developing in terms of spatial planning, and the area is a tourism area, residential area, government area, office services area, trade services area, health area and metropolitan development area. Figure 1 shows the seismotectonic condition of Bengkulu Province, which includes the Sumatran Fault, Mentawai Fault, and Sumatra Subduction Zone, as well as the investigated location flank. The activity of the Sumatra Subduction Zone, Mentawai Fault and Sumatra Fault can trigger earthquakes in Bengkulu Province and the surrounding area. For this reason, Bengkulu Province is one of the regions in Indonesia that is very prone to earthquake disasters. The investigated locations recorded from PU-1 to PU-6 represent the respective district areas. PU-1 to PU-3 sites are located in North Bengkulu Regency, and PU-4 to PU-6 sites are in Central Bengkulu Regency.

Mase (2017) conducted research on liquefaction in coastal areas of the Province using the concept of seismic wave propagation. The research results show that Bengkulu City is one of the areas heavily affected by liquefaction due to the 2007 earthquake. Mase

Figure 1 Seismotectonic Conditions in Bengkulu Province and The Investigated Location.

(2017) presents an interpretation of ground movements and a comparison of response analysis due to the 2007 Bengkulu-Mentawai earthquake in the Muko-Muko Regency. Previous research has not explicitly analysed the seismic response using equivalent linear and nonlinear comparisons in the Central Coastal area of Bengkulu Province. In their research, Mase (2017) stated that seismic response analysis propagates one-dimensional seismic waves through horizontal soil layers. One-dimensional seismic response analysis is used to resolve the vertical propagation of horizontal shear waves through soil layers (Hashash, 2016). Several models are commonly used in analysing seismic response, namely linear and nonlinear equivalent models. Using linear equivalent assumptions, the linear equivalent model approximates nonlinear shear stresses and shear strains. Misliniyati et al. (2019) conducted a validation study of linear elastic models, equivalent linear models, and nonlinear models in soil seismic response analysis. Seismic response analysis begins by propagating seismic waves through the bedrock to the ground surface (Qodri et al., 2021). Seismic response analysis produces spectral response parameters. Spectral response is one of the essential seismic parameters in the design of earthquake-resistant buildings (Aprillianto et al., 2016). The resulting spectral response includes Peak Ground Acceleration (PGA), time story acceleration, spectral response acceleration and amplification factor.

Peak Ground Acceleration (PGA) or maximum ground acceleration is the maximum value of ground acceleration in an area caused by earthquake vibrations during a specific period (Al Ayubi et al., 2020). The maximum ground acceleration value is influenced by earthquake waves propagating through the ground and the nature of the soil layers in the area (Widyawarman and Fauzi, 2020). The maximum ground acceleration value can mean that the greater the acceleration value, the more significant the impact of the earthquake risk that may occur (Suhartini et al., 2019).

The acceleration of the spectral response, a key parameter in the design of earthquake-resistant buildings, can be used to carry out structural analysis. This spectral response can describe the natural period of a building structure simply by estimating the level of the building. The resulting spectral response design results can provide building design recommendations that better consider the influence of earthquake loads. This practical implication of the research underscores its relevance to seismic analysis and earthquake engineering, providing valuable insights for designing and constructing earthquake-resistant structures in the Central Coast area of Bengkulu Province.

Amplification factor shows the change in ground acceleration due to an earthquake from the bedrock to the ground surface. The difference in shear wave velocity (Vs) in the bedrock and each soil layer causes amplification. The Vs value from the bedrock to the surface could generally get smaller. The smaller the Vs value, the smaller the shear modulus (G) and damping factor (ξ). This is what causes the acceleration of the ground to increase. A greater value of the amplification factor indicates a more significant acceleration of ground movement on the surface (Partono et al., 2013).

This research analyses the seismic response that produces Peak Ground Acceleration (PGA), acceleration time history, acceleration response spectra, and amplification factors. In addition, the acceleration spectra at the ground surface obtained from the analysis results are compared with those designed by *SNI 1726* (2019).

2 METHODS

2.1 Soil Layers

Figure 2 Site Investigation result: The soil layer in this research area is generally dominated by sand. The soil layer is dominated by sand because it is located in a coastal area. This soil layer of sand has the property of dampening vibrations before they reach the building. The National Earthquake Hazard Reduction Program (NEHRP) categorises this research area at points PU-1 to PU-5 as medium ground (site class D) with the time average shear wave velocity for the first 30 m depth (Vs_{30}), namely 180-360 m/s and PU-6 as hard soil (site class E) with Vs_{30} of 360-760 m/s.

2.2 Earthquake Wave

The input earthquake wave propagated is the scaled 2007 Bengkulu-Mentawai earthquake wave developed by Mase (2017). Figure 3 shows earthquake wave data with a PGA value of 0.33, which is used as input movement to analyse one-dimensional linear and nonlinear earthquake wave propagation using the Pressure Dependent Hyperbolic (PDH) model.

2.3 Earthquake Wave Propagation

The wave propagation model used is the Pressure-Dependent Hyperbolic (PDH) Model. The data used for modelling are primary soil layer data and scaled 2007 Bengkulu-Mentawai earthquake wave data (Mase, 2017) as motion input. The wave propagation scheme is presented in Figure 4. Waves are propagated from the bedrock to the ground surface, where seismic wave propagation is analysed.

Seismic wave modelling is carried out through several stages. Analysis of the soil profile created by inputting physical and dynamic soil parameters. Using reference curves, dynamic parameters such as shear modulus ratio (G/G_{max}) are determined based on soil type. Granular soils use the G/G_{max} curve of Seed (1970), while cohesive soils use the G/G_{max} curve of Vucetic and Dobry (1991). The estimated curve for the equivalent linear and nonlinear shear modulus can be seen in Figure 5. The input bedrock parameters are soil volume weight (γ_{sat}) and shear wave velocity (Vs). 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). Finally, the data that has been input is run and analysed.

This analysis uses data to produce Peak Ground Acceleration (PGA) values, acceleration time history, acceleration response spectra, and amplification factors. After obtaining these values, equivalent linear and nonlinear values are compared.

3 RESULT AND DISCUSSION

3.1 Peak Ground Acceleration (PGA)

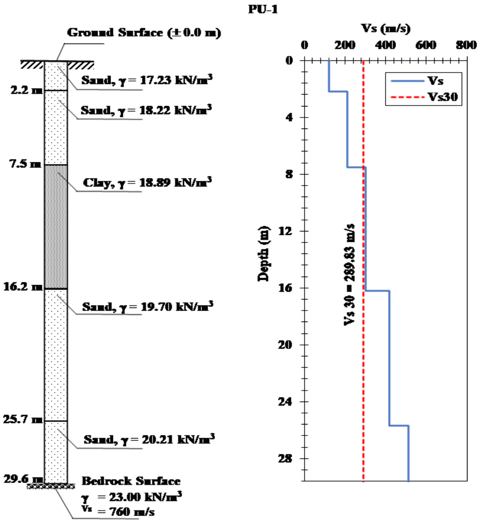
The maximum acceleration of each layer resulting from seismic response analysis in graphical form can be seen in Figure 6. The PGA value functions to determine the level of earthquake risk with a PGA value of 0.3g-0.4g, including high risk, and a PGA value > 0 .4g is considered a very high risk (Fathani et al., 2006). The highest PGA value is found in the surface layer, while the lowest PGA value is found in the bottom layer. Referring to research by Fathani et al. (2006), the nonlinear PGA value PU-1 to PU-6 is in the range 0.20g-0.52g, and the equivalent linear PGA is in the range 0.32g-0.63g, so it is included in the category of areas that have a very high risk of earthquake. Equivalent linear has a higher value compared to nonlinear. This aligns with research by Mase (2020), in which linear equivalents can produce PGA values that exceed actual estimates and indicate a reasonably large overestimate.

3.2 Time History Acceleration

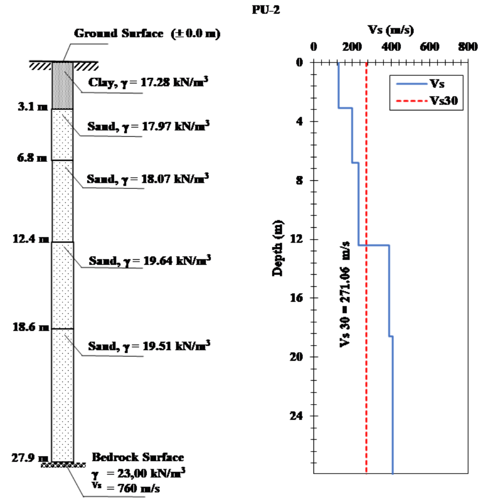
Time history acceleration is produced in graphical form, as in Figure 7. The nonlinear method earthquake wave acceleration value is in the range 0.20g-0.52g, and the linear equivalent method is in the range 0.32g-0.63g. The most significant time history acceleration value for the linear equivalent method is at Point PU-1 at 0.63g, and the lowest is at Point PU-5 at 0.32g. The most considerable nonlinear method time history acceleration value is at Point PU-1 at 0.52g and the lowest at Point PU-4 at 0.20g. Based on the analysis results, wave propagation results based on the linear equivalent approach tend to produce a more excellent maximum acceleration than the nonlinear approach. According to Mase (2018*b*), this is due to an overestimation of the shear stress, which also causes a higher PGA value. 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. Similar things were also reported by Adampira et al. (2015); Yunita et al. (2015) for case studies of soil layers in Iran and Turkey.

3.3 Spectral Response Acceleration

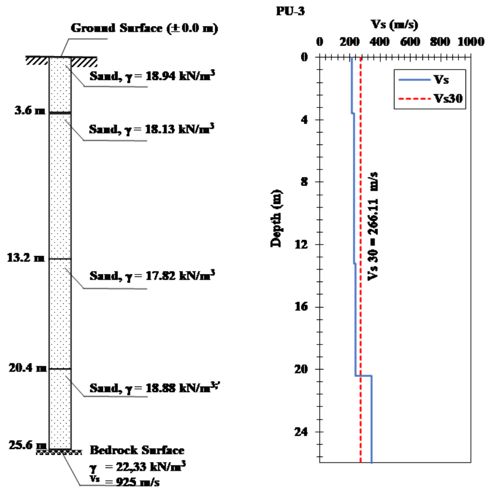
Analysis of equivalent linear and nonlinear seismic responses produces acceleration spectra with varying values for each period, as seen in Figure 8. A comparison of acceleration spectra from the analysis and design



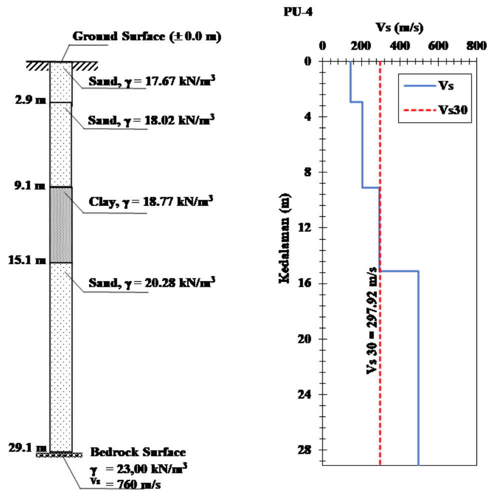
(a) PU-1



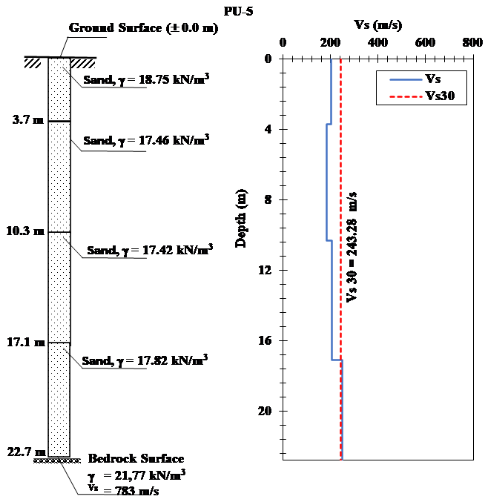
(b) PU-2



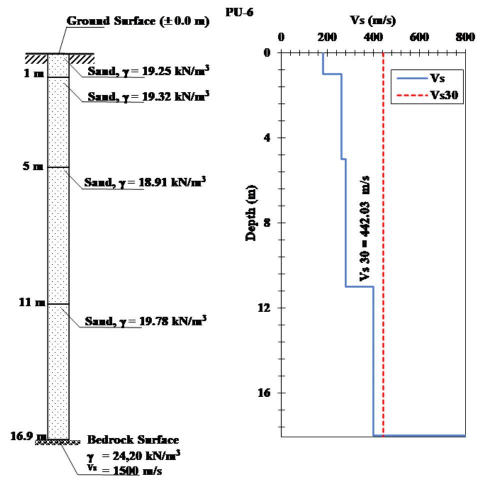
(c) PU-3



(d) PU-4



(e) PU-5



(f) PU-6

Figure 2 Seismotectonic Site Investigation Result.

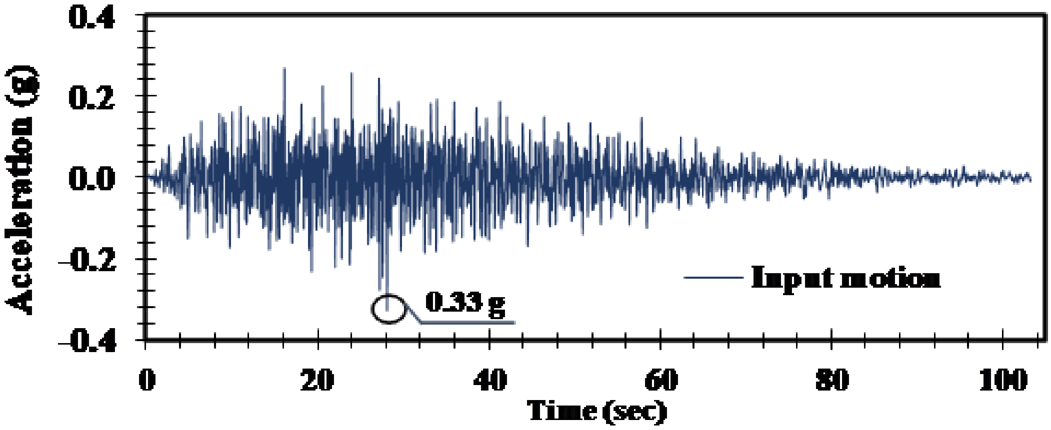


Figure 3 Scaled Input Motion (Mase, 2017).

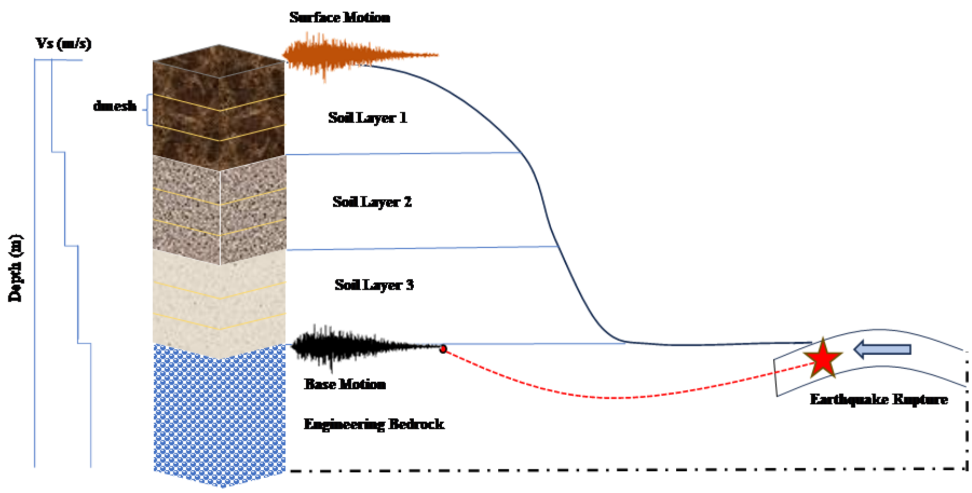


Figure 4 Wave Propagation Scheme.

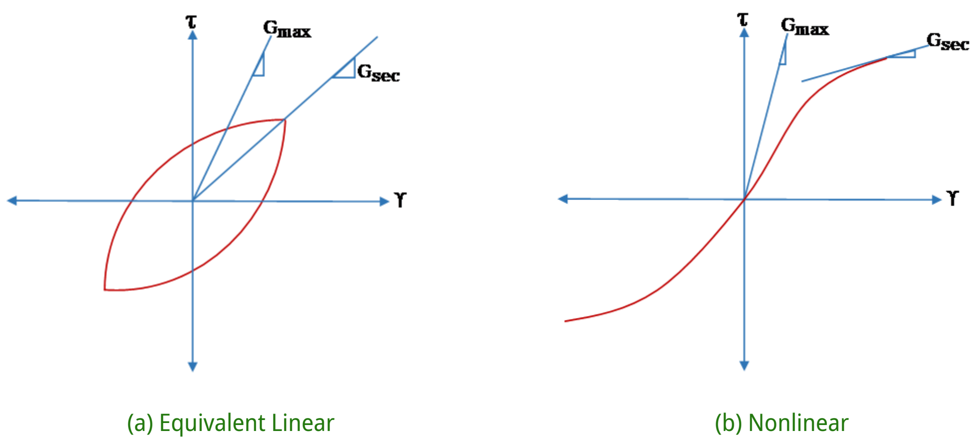
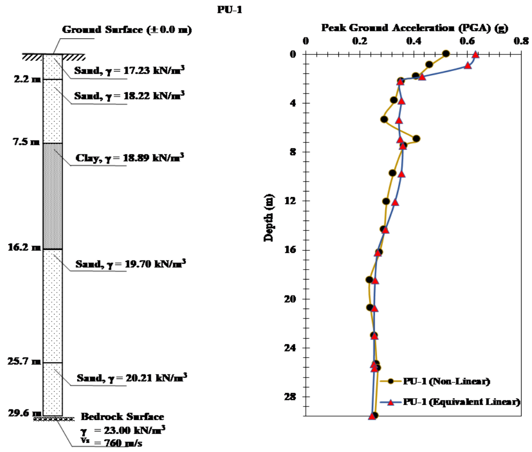
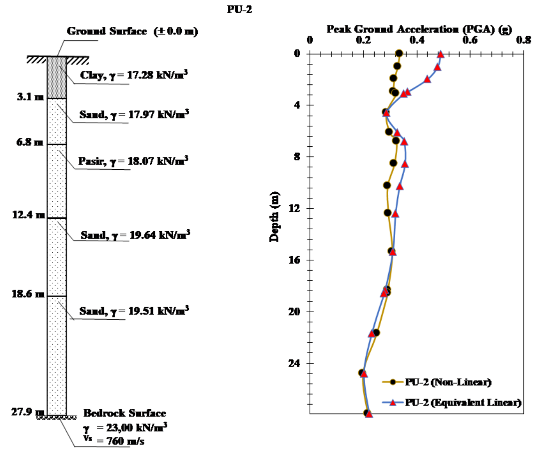


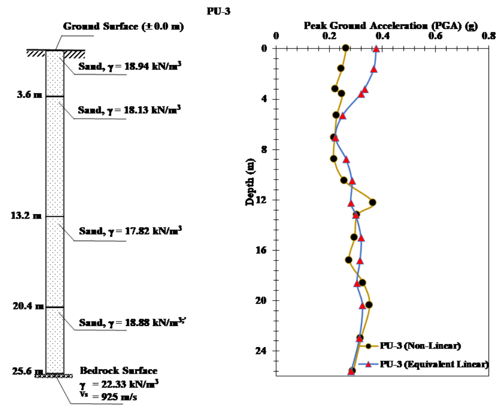
Figure 5 Shear Modulus Estimation Curve.



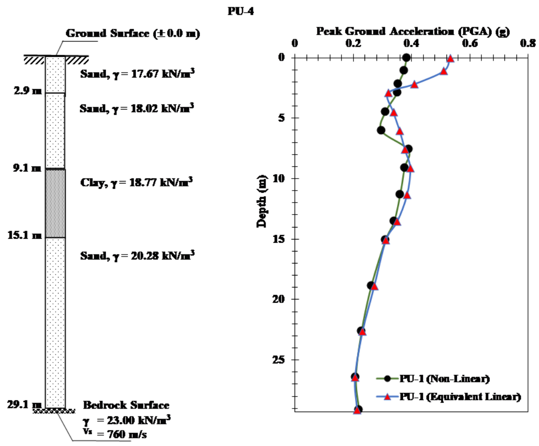
(a) PU-1



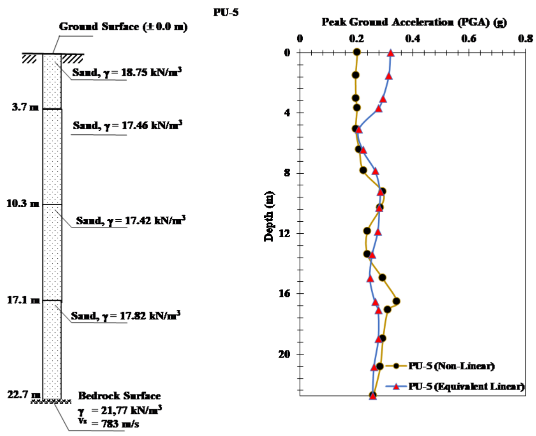
(b) PU-2



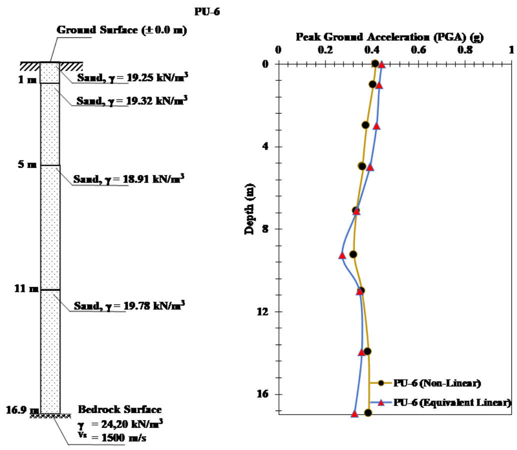
(c) PU-3



(d) PU-4

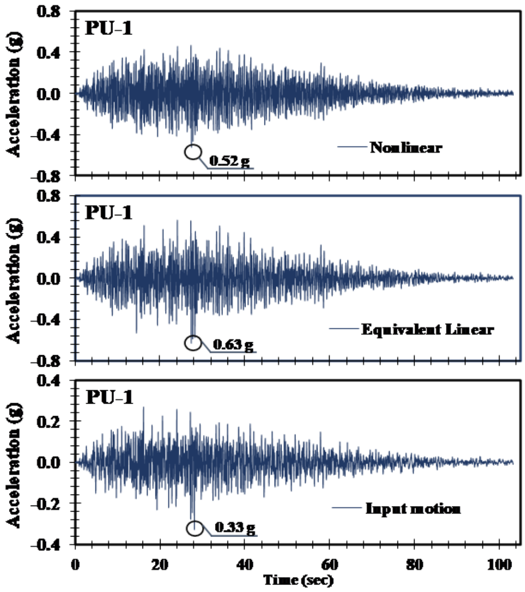


(e) PU-5

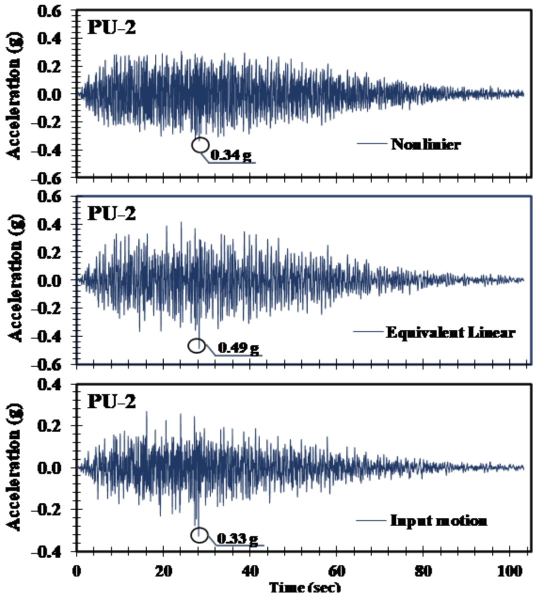


(f) PU-6

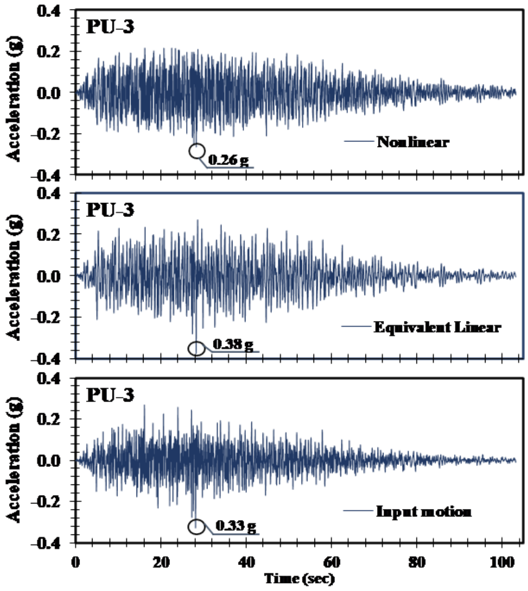
Figure 6 Peak Ground Acceleration (PGA) of Equivalent Linear and Nonlinear.



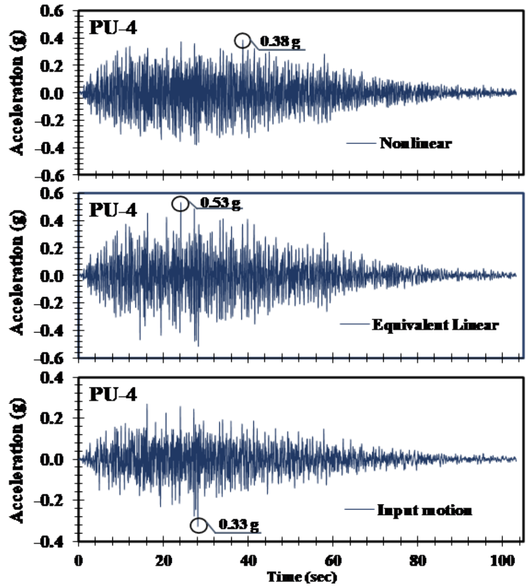
(a) PU-1



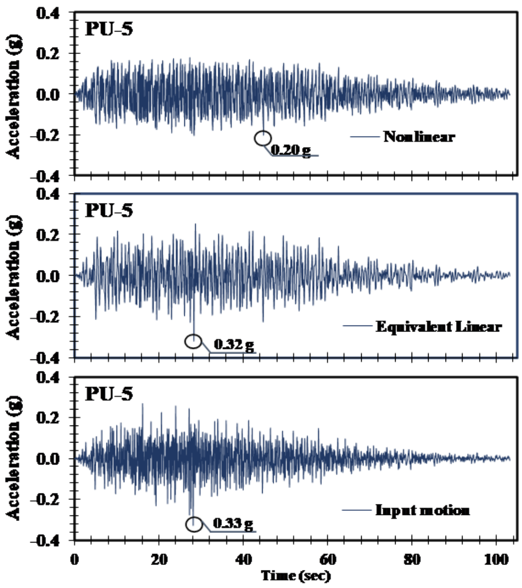
(b) PU-2



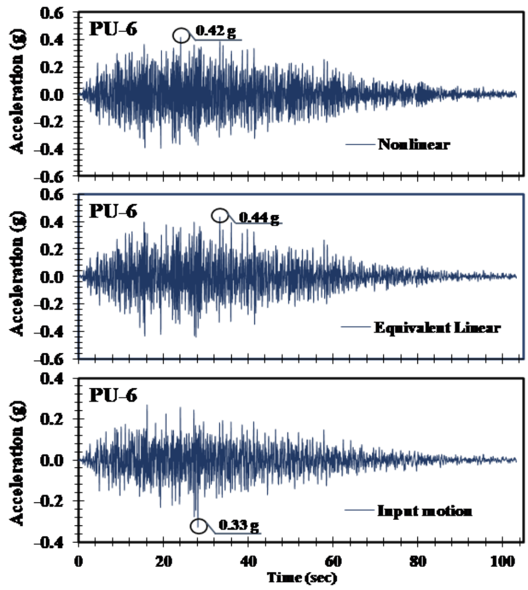
(c) PU-3



(d) PU-4

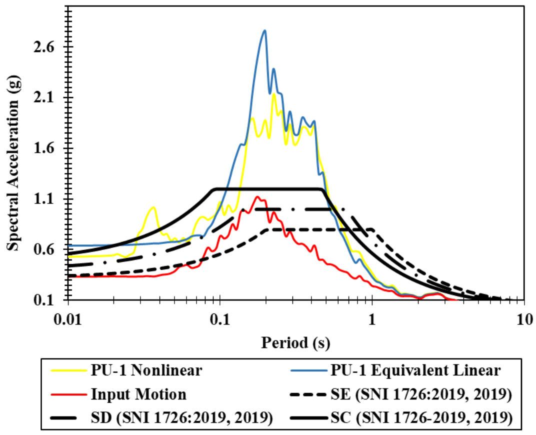


(e) PU-5

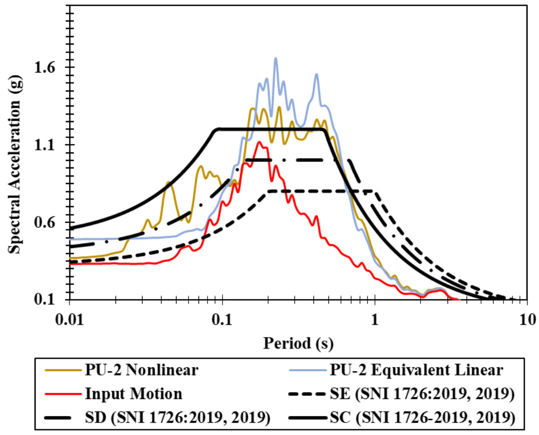


(f) PU-6

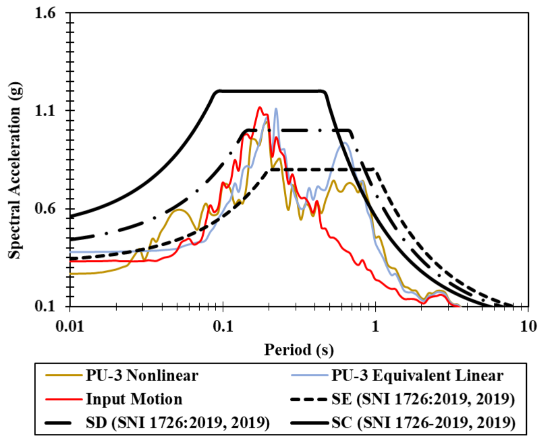
Figure 7 Time History Acceleration of Equivalent Linear, Nonlinear and Input Motion.



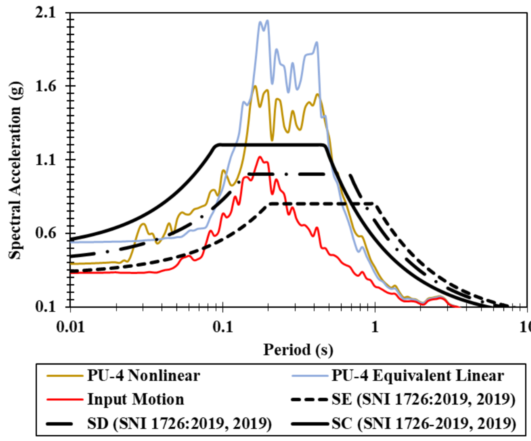
(a) PU-1



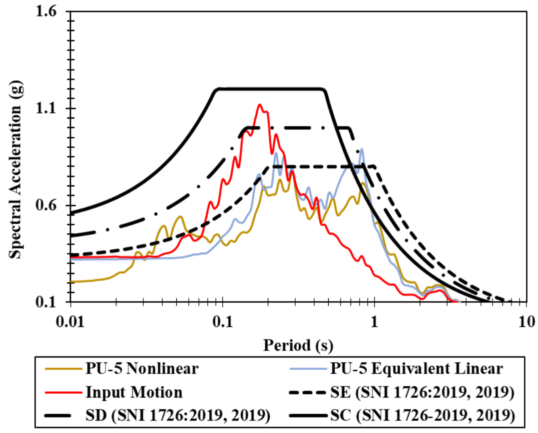
(b) PU-2



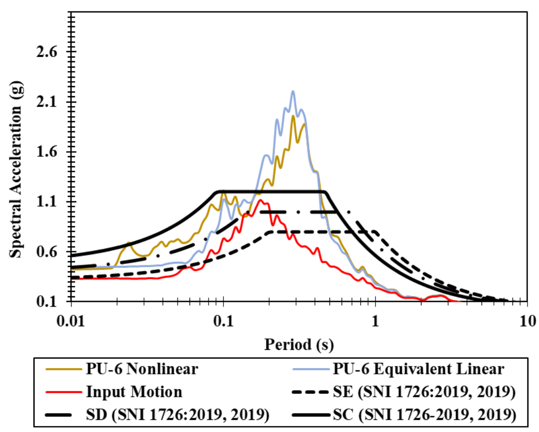
(c) PU-3



(d) PU-4



(e) PU-5



(f) PU-6

Figure 8 Spectral Acceleration.

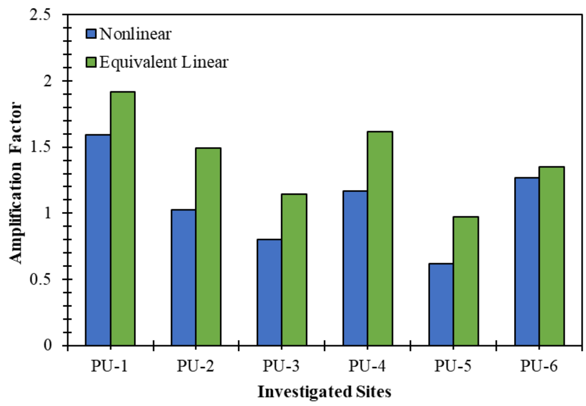


Figure 9 Comparison of Equivalent Linear and Nonlinear Amplification Factor.

of *SNI 1726* (2019) acceleration spectra is presented. The analysis's nonlinear and linear equivalent 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 the short-period design spectrum is 0.2 to 0.9 seconds. According to the Council (2017), this period range is included in the low to high building category. This shows that PU-1 to PU-6 sites are relatively unsafe when shaking due to an earthquake in both low and high-story buildings. If things like this are not reviewed, they cause quite a significant risk to buildings in that area.

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 Vs in each soil layer causes this difference. The shear wave velocity (Vs) at the ground surface tends to be smaller, so the value of the amplification factor becomes larger. 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 0.80-1.59, while the linear equivalent amplification factor ranges from 1.59-1.91. 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

Seismic response analysis in the Central Coast region of Bengkulu Province, selected in North Bengkulu and Central Bengkulu Regencies, produced high average Peak Ground Acceleration (PGA) values, time history acceleration, spectral response acceleration, and amplification factor. This condition has the potential to cause building damage. Apart from that, the potential for a sand layer that has a low density can result in consequences in the form of low soil carrying capacity and liquefaction. Studies related to liquefaction potential in coastal areas are going to be presented in future research.

Seismic response analysis also compares linear and nonlinear equivalent values for Peak Ground Acceleration (PGA), time history acceleration, spectral response acceleration, and amplification factor. The resulting linear equivalent value tends to be higher than the nonlinear value. In its application, the equivalent linear method is better used when the earthquake waves are small. Meanwhile, when the earthquake velocity tends to be significant, it is better to use nonlinear values. Therefore, it is recommended that nonlinear analysis be performed for design and evaluation purposes in locations with infrastructure. This research has not considered the buildings at the research location. The results of this research can be used as information in conducting building assessments in the area studied. Related studies can be presented in future studies.

DISCLAIMER

The authors declare no conflict of interest.

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