

Probabilistic Liquefaction Potential Mapping in South Lebong Based on PSHA-Derived PGA

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Abstract – This study evaluates liquefaction potential in South Lebong Subdistrict, Lebong Regency, Bengkulu Province, which is located in an active tectonic region influenced by the Sumatra Fault system and dominated by alluvial deposits. A probabilistic approach using the Probabilistic Seismic Hazard Analysis method to determine Peak Ground Acceleration (PGA) values for 10% and 2% probabilities of exceedance in 50 years, representing moderate to extreme earthquake conditions. South Lebong District is dominated by PGA values greater than 0.8g, particularly under the 2% probability scenario, indicating relatively high seismic hazard in the study area. Under the 10% probability scenario, several locations still show PGA values ranging from 0.4g to 0.8 g. The obtained PGA values were subsequently used to evaluate liquefaction potential through calculations of the Cyclic Stress Ratio (CSR), Cyclic Resistance Ratio (CRR), and Factor of Safety (FS). Additionally, susceptibility was assessed using the Liquefaction Potential Index (LPI) method. The results indicate that higher PGA values under the 2% probability scenario increase seismic loading intensity and liquefaction susceptibility within the study area. Based on the LPI classification, liquefaction potential under the 10% probability scenario is generally categorized as low to moderate, whereas under the 2% probability scenario, several locations shift into the moderate to severe liquefaction category. These findings indicate that liquefaction susceptibility in the South Lebong District is strongly influenced by the interaction between earthquake loading intensity and local geotechnical conditions. Therefore, the results of this study can support earthquake hazard mitigation planning and the development of safer areas that are less vulnerable to liquefaction hazards.

Keywords: Liquefaction Potential Index (LPI); Peak Ground Acceleration (PGA); PSHA OpenQuake; South Lebong; Bengkulu

I. INTRODUCTION

Indonesia is one of the most seismically active regions in the world due to its location at the convergence of several active tectonic plates. This tectonic setting results in frequent earthquakes with various source mechanisms that have the potential to cause significant damage to infrastructure and the environment. In general, earthquakes in Indonesia are relatively frequent and pose a considerable risk to infrastructure, the environment, and human life (Hutchings & Mooney, 2021).

At the regional scale, South Lebong, Lebong Regency, Bengkulu Province, is one of the areas with high seismic potential, as it is traversed by the Ketahun Fault, which is part of the Sumatra Fault system. The presence of this active fault increases the likelihood of shallow crustal earthquakes that may trigger secondary hazards such as landslides and environmental damage (Hadi et al., 2025).

In seismic-prone regions, liquefaction is one of the most critical geotechnical hazards, contributing significantly to earthquake-induced damage. This phenomenon plays a significant role in causing damage during earthquakes, including ground subsidence, surface cracking, and lateral spreading (Mase et al., 2022). Liquefaction is a geotechnical phenomenon in which loose, saturated, particularly non-cohesive soils lose their shear strength and stiffness due to earthquake-induced vibrations, causing the soil to behave like a liquid (Ahamad et al., 2025).

The response of soils to seismic loading in geotechnical engineering is strongly influenced by

the effective stress state. The effective stress is the main parameter controlling the soil's shear strength. This reduced effective stress reduces the load-carrying capacity of the soil and increases the risk of soil failure (Valetta et al., 2025). The main process responsible for reducing effective stress and causing liquefaction is the increase of pore water pressure during earthquakes.

The liquefaction potential is generally assessed empirically based on cyclic stress conditions. This empirical procedure usually compares the Cyclic Resistance Ratio (CRR) with the Cyclic Stress Ratio (CSR) to determine the safety factor (SF). These two parameters are of vital importance for liquefaction analysis. The CRR is the soil's resistance to liquefaction, and the CSR is the cyclic load on the soil due to earthquake-induced actions (Berkat et al., 2024). The interaction of these parameters provides the basic basis for assessing the liquefaction susceptibility of a region.

The reliability of the liquefaction assessment, however, is strongly dependent on the representation of the seismic hazard. In the past, studies of liquefaction analysis have generally relied on deterministic approaches that consider a single earthquake scenario. The limitation is the ability to capture the seismic hazard variability and uncertainty (Sianko et al., 2025). Therefore, probabilistic approaches are more appropriate for representing seismic hazard variability. In this context, Probabilistic Seismic Hazard Analysis (PSHA) provides a more comprehensive framework for characterizing seismic hazard uncertainty and variability (Purba et al., 2024; Silva et al., 2020).

In this study, PSHA was conducted using the OpenQuake Engine software to obtain ground-motion parameters. PSHA calculations using the OpenQuake Engine produced peak ground acceleration (PGA) and spectral acceleration values (Hielmy & Rajagukguk, 2025). These parameters are essential inputs for evaluating seismic demand in geotechnical analysis. Previous studies also indicate that GMPE-based PSHA in the Bengkulu region yields relatively high PGA values, particularly in Lebong and Kepahiang Regencies, reaching 1.8433 g and 1.8070 g, respectively (Azwar et al., 2022), indicating a high level of seismic hazard in the study area.

Index-based methods are widely employed to assess spatial susceptibility to liquefaction. Also, the Liquefaction Potential Index (LPI) approach was used in this study to assess the magnitude of liquefaction potential, thereby providing a more comprehensive picture of the geographical liquefaction susceptibility (Agustina & Karlinasari 2024). This approach generates spatial distribution of liquefaction susceptibility using soil properties and seismic loads.

There has also been some research based on LPI in some regions of Bengkulu Province. An analysis of liquefaction potential with LPI has also been conducted in the capital city of Bengkulu Province (Mase, 2024). In addition, local site conditions such as groundwater depth play a significant role in liquefaction susceptibility. Shallow groundwater levels can increase the risk of soil deformation due to liquefaction (Misliniyati et al., 2025), as they accelerate pore pressure build-up during seismic shaking. Historical earthquakes further underscore the relevance of liquefaction hazards in this region. One significant event was the 2007 Bengkulu Mentawai earthquake (Mw 8.6), which caused infrastructure damage and triggered liquefaction in several locations (Farid et al., 2024).

Previous studies in Indonesia have generally examined seismic hazard analysis and liquefaction susceptibility separately. In Bengkulu province, particularly in South Lebong District, studies integrating probabilistic seismic hazard analysis (PSHA) using OpenQuake with Liquefaction Potential Index (LPI)-based evaluation remain limited.

Therefore, this study proposes an integrated probabilistic framework combining OpenQuake-based PSHA and LPI analysis to produce a more comprehensive spatial assessment of liquefaction potential. The scientific contribution of this study lies in the integration of OpenQuake-derived probabilistic seismic parameters with LPI-based liquefaction assessment for regional-scale hazard mapping in South Lebong. The results are expected to support disaster mitigation planning and seismic risk reduction in earthquake-prone areas.

Therefore, this research aims to analyse and map the liquefaction potential of South Lebong District by combining the Probabilistic Seismic Hazard Analysis (PSHA) with OpenQuake and an assessment based on the Liquefaction Potential Index (LPI) with several scenarios of earthquake probability. In this study, the vulnerability of soil to liquefaction is evaluated by combining the earthquake hazard parameters derived from PSHA and the geotechnical characteristics from Cone Penetration Test (CPT) data. In addition, this study is also expected to provide a better understanding of the spatial distribution of liquefaction vulnerability in South Lebong District, which can be used to mitigate earthquake hazards and plan regional development in earthquake-prone areas.

II. METHODS

2.1 Research Framework

This study employs a probabilistic approach to analyze earthquake hazards in South Lebong District, Lebong Regency, utilizing geotechnical

data from previous research through the application of the Probabilistic Seismic Hazard Analysis (PSHA) method supported by OpenQuake software.

The Probabilistic Seismic Hazard Analysis (PSHA) was conducted using the OpenQuake Engine software to estimate seismic hazard parameters in the study area. The analysis considered probabilities of exceedance of 2% and 10% in 50 years, using Peak Ground Acceleration (PGA) as the primary intensity measure. The earthquake source model was based on the regional seismicity characteristics of the active faults and subduction source in the Sumatra region.

The selected Ground Motion Prediction Equations (GMPEs) were chosen because they are appropriate for the tectonic setting of the region of study, particularly for shallow crustal and subduction earthquake sources. The obtained PGA values were then used as input for the liquefaction potential assessment.

The PSHA analysis gives the Peak Ground Acceleration (PGA) for the return periods of 10% and 2% in 50 years. The obtained PGA values were subsequently used as loading parameters in the liquefaction potential evaluation. The liquefaction potential was evaluated by calculating the Cyclic Stress Ratio (CSR) as the seismic load, the Cyclic Resistance Ratio (CRR) as the soil's resistance capacity, and the factor of safety (FS) to evaluate the soil's vulnerability to liquefaction.

Also, the distribution of liquefaction potential is assessed using the Liquefaction Potential Index (LPI) to express the overall degree of liquefaction vulnerability in the study area (Iwasaki et al., 1984; Maurer et al., 2014).

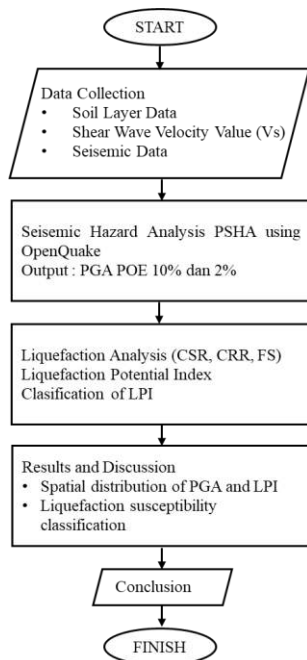


Figure 1. Research Methodology Framework

2.2 Research Location

The survey locations in this study were determined based on soil survey data from a previous study in Lebong Regency, South Lebong District. Figure 2 shows the distribution of research locations and survey points.

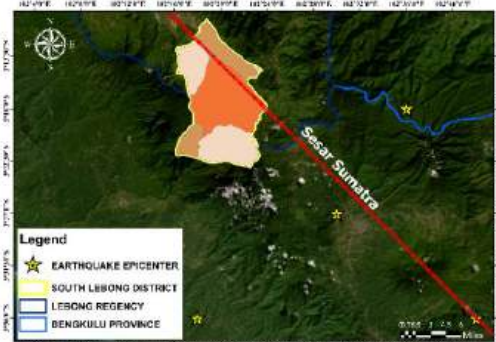


Figure 2. Research location in South Lebong District

Figure 2 represents the study area in South Lebong District for the purpose of seismic hazard and liquefaction potential assessment.

2.3 Data Collection and Analysis

This research uses secondary data from previous research on the South Lebong District. The data used includes the CPT test results, geotechnical characteristics and geological conditions. The data were utilized for the use of soil profiles and shear wave velocity (V_s) for the estimation of liquefaction potential.

In general, lower shear wave velocity values mean softer soil conditions and a higher probability of amplification during an earthquake. The higher the magnitude of shear wave velocity, the denser and stiffer the soil condition. The simultaneous use of these characteristics permits a more complete identification of the subsurface conditions and a more precise evaluation of the liquefaction susceptibility.

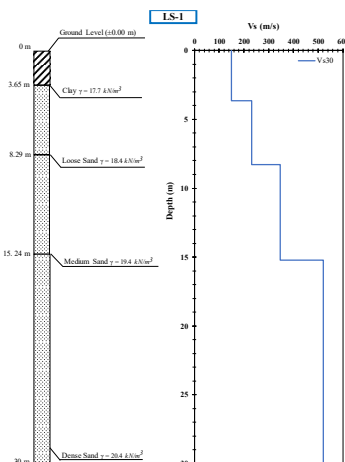


Figure 3. Soil Profile and shear wave velocity profile at LS-1 South Lebong District.

The soil profile and shear wave velocity profile at the LS-1 location are shown in Figure 3. Lower shear wave velocities near the top suggest comparatively softer soil conditions than deeper levels.

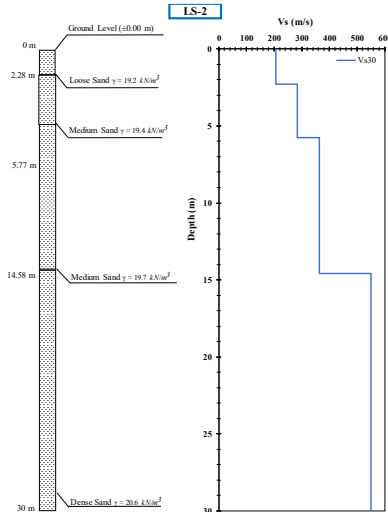


Figure 4. Soil Profile and shear wave velocity profile at LS-2 South Lebong District

Figure 4 presents the soil profile and shear wave velocity profile at the LS-2 location. The fluctuations of soil layer and shear wave velocity data show the variation of the subsurface conditions in South Lebong District.

Data processing of cone tip resistance, interpretation of soil behavior type and estimation of liquefaction resistance parameters. The adjusted cone resistance measurements were then used for calculating the Cyclic Resistance Ratio (CRR) for liquefaction evaluation.

The values of Peak Ground Acceleration (PGA) derived from PSHA analysis were used as key input for liquefaction assessment by calculating the Cyclic Stress Ratio (CSR), Cyclic Resistance Ratio (CRR), and Factor of Safety (FS).

The factor of safety against liquefaction was evaluated using Equation (1).

$$FS = \frac{CRR}{CSR} \quad (1)$$

The FS value is used to determine liquefaction potential; $FS \leq 1$ indicates that the soil has the potential to liquefy.

Next, the distribution of liquefaction potential is analyzed using the Liquefaction Potential Index method.

The liquefaction Potential Index (LPI) was calculated using Equation (2).

$$LPI = \int_0^{20} F(z)w(z)dz \quad (2)$$

The Liquefaction Potential Index (LPI) is used to describe the overall level of liquefaction vulnerability in the study area by integrating variations in soil resistance with depth and the influence of each layer on liquefaction potential (Iwasaki et al., 1984; Maurer et al., 2014). Soil is more susceptible to liquefaction with the higher LPI value and is relatively more stable with the lower LPI value.

III. RESULTS AND DISCUSSION

3.1 Peak Ground Acceleration (PGA)

The results of earthquake hazard analysis using the method of Probabilistic Seismic Hazard Analysis (PSHA) with the help of software OpenQuake show the distribution of Peak Ground Acceleration (PGA) values in the South Lebong District for a probability level of 10% and 2% with a return period of 50 years. These two levels of probability correspond to earthquake conditions ranging from moderate to extreme seismic intensity and hence provide an overview of the possible variations in seismic loading in the study area. The spatial distribution of the PGA values is shown in the form of maps to represent the patterns of the earthquake hazard at each observation location.

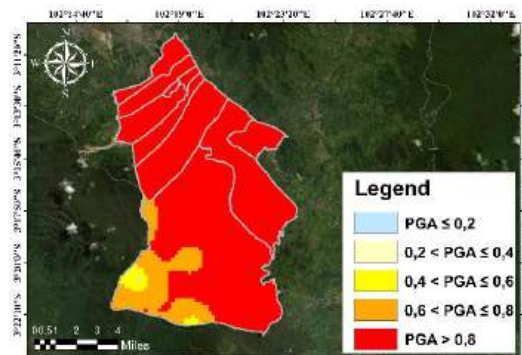


Figure 5. Peak Ground Acceleration (PGA) distribution for 10% Probability of exceedance in 50 years in South Lebong District

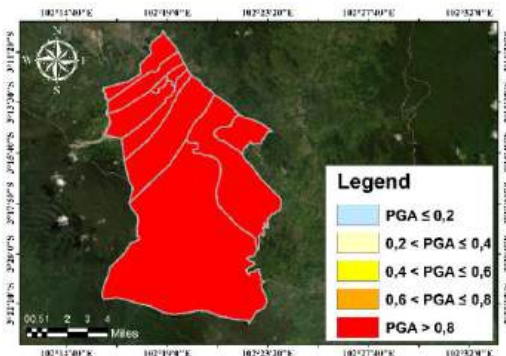


Figure 6. Peak Ground Acceleration (PGA) distribution for 2% Probability of exceedance in 50 years in South Lebong District

The obtained PGA values indicate variations in seismic hazard levels across the study area. Under the 2% probability scenario, several locations exhibit significantly higher PGA values compared to the 10% probability scenario, indicating stronger seismic loading under extreme earthquake conditions.

Based on Figures 5 and 6, the distribution of PGA values in South Lebong District exhibits significant spatial variation. At a 10% probability, PGA values tend to be lower and more uniform across most of the region, reflecting more frequent earthquakes with lower energy levels. In the 2% probability scenario, higher PGA values are observed at several locations, indicating the influence of lower-frequency, higher-intensity earthquake events.

Based on the PGA classification shown in Figures 5 and 6, most areas in South Lebong are dominated by PGA values greater than 0.8 g, particularly under the 2% probability scenario. It indicates relatively high seismic hazard in the study area. In the case of 10% probability, several places still have the value of 0.4 g to 0.8 g. But the spatial distribution is rather more uniform than the 2% probability case.

The distribution of PGA spatial variations is attributed to the distance from the earthquake source, seismic source characteristics and local geological conditions. PGA values are generally greater in the proximity of active fault zones and, in particular, in portions of the Sumatra Fault system compared to sites that are more distant. Surface geological variables also influence the amplification and modification of seismic waves as the waves propagate from the earthquake source to the ground surface.

The relatively high PGA values obtained in this study are in accordance with previous studies of seismic hazards in Bengkulu Province, which reported high PGA values in Lebong Regency due to the influence of the Sumatra Fault system and regional tectonic activity (Azwar et al., 2022). This indicates that the South Lebong District is in a seismically active zone with high earthquake hazard.

In addition to source distance and geological conditions, local soil characteristics also affect variations in PGA values. Softer soil conditions with lower shear-wave velocities tend to amplify ground shaking, whereas denser and stiffer soils tend to show lower amplification effects. Therefore, sites at similar distances from earthquake sources might have different PGA values because of varying local geotechnical properties.

The liquefaction potential is of importance because the increase in the PGA value under the 2% probability scenario has important implications for liquefaction assessment. The increase in PGA values

will increase the Cyclic Stress Ratio (CSR), which may reduce the Factor of Safety (FS) against liquefaction and increase the possibility of soil failure during seismic events. Therefore, the PGA distribution derived from the PSHA analysis server is a crucial parameter for the liquefaction susceptibility assessment in the study area.

In summary, the results show that the level of seismic hazard in the South Lebong District varies spatially, with a significantly higher hazard potential for extreme earthquake scenarios. Therefore, the obtained PGA distribution provides important information for seismic hazard mitigation, earthquake-resistant infrastructure planning, and regional liquefaction susceptibility assessment in South Lebong District.

3.2 Liquefaction Potential Index (LPI)

Based on the Peak Ground Acceleration (PGA) values obtained from the PSHA analysis at 10% and 2% probability levels over a 50-year return period, the evaluation was performed using the Liquefaction Potential Index (LPI) method. This method was applied to describe in depth the contribution of each soil layer to liquefaction potential. The calculated LPI values were subsequently visualized as spatial distribution maps for both probability scenarios.

To interpret the level of liquefaction based on the LPI values, the liquefaction potential classification proposed by (Maurer et al., 2014) is used as shown in Table 1. Based on this classification, LPI values < 4 indicate no liquefaction potential, values between $4 \leq \text{LPI} < 8$ indicate marginal liquefaction potential, $8 \leq \text{LPI} < 15$ indicate moderate liquefaction potential, and values greater than or equal to $\text{LPI} \geq 15$ indicate severe liquefaction potential.

Table 1. Classification of liquefaction potential based on LPI values

LPI Ranges	Susceptibility Level
$\text{LPI} < 4$	No liquefaction
$4 \leq \text{LPI} < 8$	Marginal liquefaction
$8 \leq \text{LPI} < 15$	Moderate liquefaction
$\text{LPI} \geq 15$	Severe Liquefaction

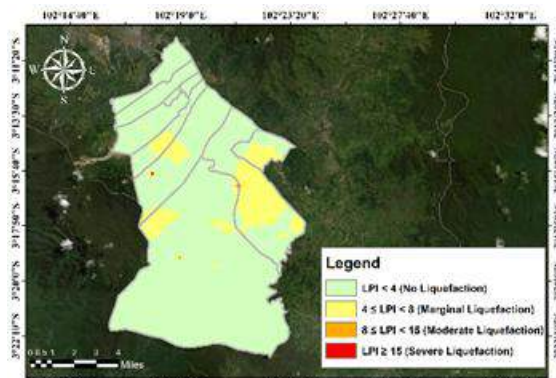


Figure 7. LPI distribution for 10% Probability of exceedance in 50 years in South Lebong District

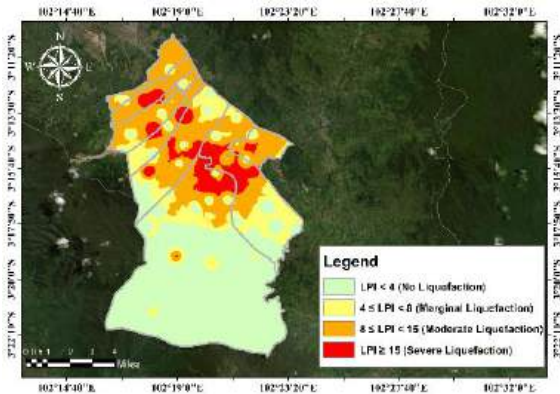


Figure 8. LPI Distribution for 2% Probability of exceedance in 50 years in South Lebong District

Based on Figure 7, the distribution of LPI values under the 10% probability scenario indicates that most areas in South Lebong District fall within the low to moderate liquefaction susceptibility category. Areas with LPI values less than 5 usually indicate low liquefaction potential, and areas with LPI values between 5 and 15 indicate moderate liquefaction susceptibility. The higher LPI values are seen only in a few places, which are indicative of localized areas with higher liquefaction susceptibility.

Figure 8 illustrates an increase in LPI values under the 2% probability scenario across several parts of the study area. Locations that were previously classified as having low and moderate susceptibility generally shifted to higher liquefaction susceptibility levels. LPI values exceeding 15 were identified in several zones, indicating severe liquefaction susceptibility and a greater potential for surface manifestation during strong ground shaking. These findings suggest that increasing seismic intensity contributes to a higher likelihood of liquefaction occurrence in the study area.

The increase of LPI values from the 10% to the 2% probability scenario is strongly correlated with the increase of seismic loading, as indicated by the higher PGA values. The higher the PGA values increase, the Cyclic Stress Ratio (CSR), which subsequently reduces the Factor of Safety (FS) against liquefaction. As a result, more soil layers satisfy the liquefaction criterion $FS \leq 1$, thereby increasing the overall LPI values.

Spatial variations of LPI distribution are also strongly influenced by local geotechnical conditions. From the soil profiles and shear wave velocity (V_s) profiles obtained from CPT data, it is observed that the relatively loose and soft soil layers are more prone to liquefaction. Lower shear wave velocity values generally correspond to lower soil stiffness and higher amplification potential during seismic shaking and thus may increase susceptibility to liquefaction.

The results are in line with previous studies on liquefaction in Bengkulu Province, which reported

that areas with dominant loose sediment layers and high seismic loading tend to have high liquefaction susceptibility (Mase, 2024). This suggests that the local geological and geotechnical conditions play an important role in controlling the spatial distribution of liquefaction potential in South Lebong District.

In general, the LPI distribution maps generated in this study indicate that liquefaction susceptibility in South Lebong District increases significantly under extreme earthquake scenarios. Thus, the LPI obtained can be used to demarcate the liquefaction-prone zones and can help in disaster mitigation planning and the reduction of seismic risk in earthquake-prone areas.

3.3 Discussion

The result of this study reveals that the severity of the earthquake has a substantial effect on the liquefaction susceptibility in the South Lebong District. Overall, the PGA values are higher as the probability of exceedance decreases from 10% to 20% in 50 years of the return period. The increase in seismic loading then increases the Cyclic Stress Ratio (CSR) and decreases the Factor of Safety (FS) and liquefaction susceptibility as seen by higher LPI values at multiple observation stations.

Correlation between the PGA and LPI, however, does not always exhibit a directly proportional spatial pattern. Some sites with relatively high PGA values may not necessarily have high LPI values. The result shows that liquefaction susceptibility is not only controlled by seismic loading but also significantly affected by the local geotechnical conditions. Changes in liquefaction susceptibility across observation stations are due to changes in soil density, grain size distribution, stiffness and groundwater depth. Soil layers with low density and shallow groundwater conditions are likely to have higher pore water pressure during cyclic loading, which decreases the effective stress and reduces the soil resistance to liquefaction.

On the other hand, soil layers having denser and stiffer properties have greater values of Cyclic Resistance Ratio (CRR). Therefore, some places are more stable under higher PGA circumstances in the 2% likelihood case. This condition explains the spatial non-uniformity of LPI values growth throughout the studied area.

The results of this study are generally similar to previous liquefaction studies in Bengkulu Province (Mase, 2024), which found that liquefaction susceptibility tends to increase in locations with soft soil deposits and shallow groundwater conditions. These results reinforce the idea that the local site characteristics play a major role in reducing liquefaction potential in seismic-prone regions.

The overall results show that the liquefaction susceptibility in the South Lebong District is

regulated by the combination of seismic loads and local geotechnical conditions. Therefore, both aspects should be examined extensively in earthquake hazard mitigation and regional development planning, especially in liquefaction hazard susceptible locations.

IV. CONCLUSION

The increase of Peak Ground Acceleration (PGA) and local geotechnical conditions greatly affect the potential of liquefaction in the South Lebong District in this research. The findings of research show that PGA values for 2% exceedance probability are bigger than those for 10% exceedance probability, indicating a higher intensity of the earthquake and a increased likelihood of liquefaction.

The liquefaction potential is generally low to moderate, as shown by Liquefaction Potential Index (LPI) values at 10% probability. However, at 2% probability, the liquefaction potential increases to moderate to high category at many locations, which means the soil is more prone to liquefaction during extreme earthquake scenarios. Soil properties from subsurface profiles are also important factors for liquefaction susceptibility levels.

Cyclic loading can lead to deformation of relatively soft soil layers, especially fine-to medium-grained soils, more easily than denser soil deposits. Therefore, the geographic variation of liquefaction potential is the result of variation in soil conditions in the study area. The results generally show that liquefaction potential is controlled by the combined effect of seismic loading intensity and local geotechnical conditions. The results can consequently provide important information for disaster mitigation planning, earthquake resistant infrastructure development, regional spatial planning, and for the identification of places with decreased liquefaction risk.

The scientific contribution of this research is the combination of Probabilistic Seismic Hazard Analysis (PSHA) based on OpenQuake and Liquefaction Potential Index (LPI) analysis to determine liquefaction susceptibility at a regional scale in South Lebong District. This approach merges probabilistic seismic loading with local geotechnical characteristics to obtain a more complete picture of earthquake-induced liquefaction dangers in the area under consideration.

The main limitation of this study is the absence of secondary CPT data and the uneven distribution of investigation locations that may alter the portrayal of subsurface variability over the studied area. Furthermore, the analysis is essentially based on liquefaction susceptibility using the PGA values and subsurface geotechnical conditions. This study did

not include detailed site response analysis, seismic micro zonation, and further geotechnical investigation data, although these could improve the accuracy of liquefaction hazard assessment and obtain a more detailed understanding of liquefaction behavior in South Lebong District and other earthquake-prone regions. Future studies are recommended to include detailed site response analysis, seismic micro zonation, additional CPT investigations, and groundwater monitoring to improve the reliability and spatial resolution of liquefaction hazard assessment.

AUTHOR'S CONTRIBUTION

Conceptualization: DD, LZM, TBP;

Data curation: DD, LZM, TBP;

Formal analysis: DD, LZM, TBP;

Methodology: LZM, DD, TBP;

Validation: LZM;

Visualization: DD, LZM, TBP;

Writing: DD, LZM, FS, TBP, RM, KA.

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