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Zonation of Seismic Vulnerability Levels in South Bengkulu Regency, Indonesia for Disaster-Based Regional Planning

Arif Ismul Hadi[1]; M Farid[2]; Lindung Zalbuin Mase[3]; Refrizon[4]; Shela Basaria Purba[5]; Darmawan Ikhlas Fadli[6]; Erlan Sumanjaya[7]

[1] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia, https://orcid.org/0000-0002-0728-8241*

[2] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia*

[3] *Department of Civil Engineering, Faculty of Engineering, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia, https://orcid.org/0000-0002-0470-0149*

[4] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia, https://orcid.org/0000-0002-7951-640X*

[5] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia*

[6] *Department of Geophysics, Faculty of Mathematics and Natural Sciences, the University of Bengkulu, Jl. WR Supratman, Bengkulu, 38371, Indonesia, https://orcid.org/0000-0003-0383-9875*

[7] *Department of Geodetic Engineering, Faculty of Engineering, the University of Lampung, Jl. Prof. Dr. Sumantri Brojonegoro No. 1, Bandar Lampung 35141, Indonesia, https://orcid.org/0000-0001-6889-6569*

Abstract

The accurate prediction and prevention of earthquakes remains challenging. Consequently, the primary approach to mitigate the impact of earthquakes is through disaster risk reduction efforts. One significant strategy involves conducting seismic vulnerability analyses based on disaster scenarios. This study aims to identify and map areas with varying levels of seismic vulnerability, analyzing the factors contributing to vulnerability in the South Bengkulu Regency. Secondary data, including peak ground acceleration (PGA) values, were collected, along with microtremor data obtained through the Horizontal to Vertical Spectral Ratio (HVSR) method. The recorded microtremor data serve as input parameters for PGA, Modified Mercalli Intensity (MMI), Seismic Vulnerability Index (K_g), shear wave velocity (V_s), and the time-averaged shear wave velocity for the first 30 m depths (V_{s30}) values. The findings reveal that, overall, seismic vulnerability in the South Bengkulu Regency can be categorized as low. However, specific areas, particularly in the southwestern and northeastern zones, exhibit relatively higher levels of vulnerability. The heightened vulnerability in these areas is attributed to elevated PGA values, despite the region's generally high soil density, which acts as a mitigating factor against earthquake threats.

Keywords:

earthquake; disaster risk; seismic vulnerability; South Bengkulu; Indonesia

1. Introduction

Geographically, South Bengkulu Regency in Bengkulu Province, Indonesia, is situated near seismic sources, originating both from the ocean through the Indo-Australian tectonic plate movements and from the mainland through the Manna segment of the Sumatran Fault (see **Figure 1; Megawati et al., 2005; Petersen et al., 2007; PUSGEN, 2017; Hadi et al., 2021a; PUSGEN, 2022; Awaliyah et al., 2023**). The Indo-Australian tectonic plate exhibits the highest tectonic energy and strain rate in the Bengkulu Province area, including South Bengkulu Regency, making it susceptible to elevated seismic activity compared to other regions on Sumatra Island (**Murjaya, 2011; Megawati et al., 2005; PUSGEN, 2017; PUSGEN, 2022**). The presence of the Manna segment of the Sumatran Fault, considered here as the main seismogenic fault, along with secondary faults traversing South Bengkulu Regency, poses a significant earthquake threat in the surrounding areas, particularly those with high population density (**Natawidjaja and Triyoso, 2007**). The geological structure observed in this area is a fault in the general direction of southeast – northwest which is characterized by the presence of some lineaments, hills and waterfalls, faults, folds, and breakthroughs of igneous rock. The characteristics of the developing geological structure indicate

Corresponding author: Arif Ismul Hadi
e-mail address: ismulhadi@unib.ac.id

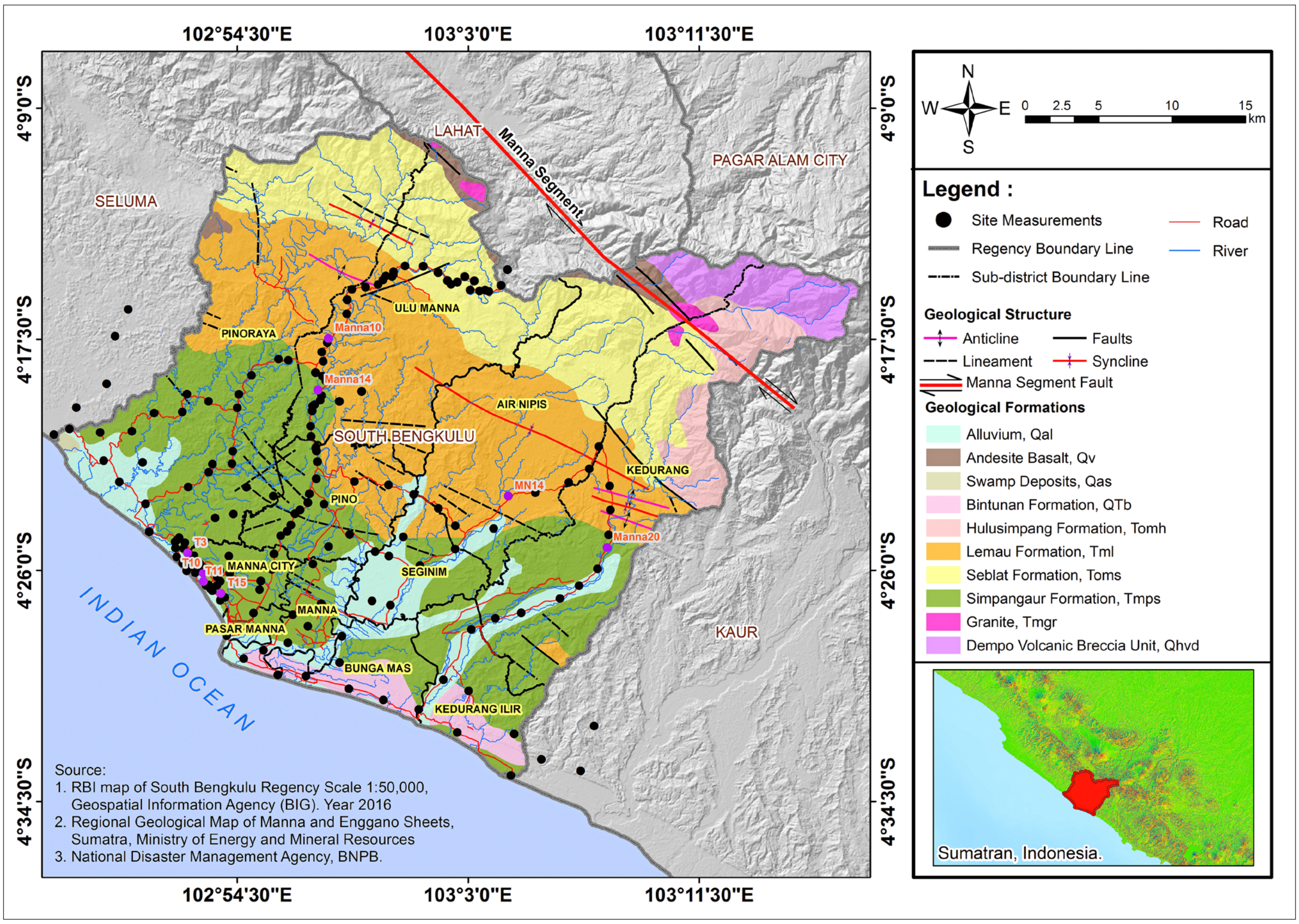

Figure 1: Simplified geological map of the South Bengkulu Regency of Indonesia (**Amin et al., 1994** and modified by **Hadi et al., 2022**)

quite active tectonic conditions (**Taufik and Rahmat, 2006**). The stratigraphy of South Bengkulu consists of Tertiary and Quaternary sequences. The Tertiary stratigraphic units are the Hulusimpang Formation (Tomh), Seblat Formation (Toms), Granite (Tmgr), Lemau Formation (Tml), and Simpangaur Formation (Tmps). The Quaternary stratigraphic units consist of the Bintunan Formation (QTb), Quartenary volcanic rock (Qv), Dempo volcanic breccia unit (Qhvd), Swamp deposit (Qas), and Alluvium (Qal) (**Amin et al., 1994**). Hulusimpang Formation (Tomh) is the oldest Tertiary sedimentary rock in the Bengkulu Basin which consists of sedimentary rocks deposited in a regression manner of Miocene age (**Heryanto, 2006; Solehan et al., 2012**). The lithology of the Hulusimpang Formation (Tomh) consists of Andesitic-basaltic lava, volcanic breccia, tuff and intercalation of sandstone, generally altered, containing quartz, veinlets and sulphide minerals (**Solehan et al., 2012**). Hulusimpang Formation (Tomh) is located to the south, center and northeast of Manna city. Additionally, the geological formations, characterized by soft rock lithologies, contribute to a heightened level of seismic vulnerability especially in rocks that have experienced weathering (**SNI, 2019; Hadi et al., 2018; Hadi et al., 2021b; Hadi et al., 2021c**). **Figure 1** shows the existence of the main Sumatran Fault in the Manna segment, secondary faults across the South Bengkulu Regency, and their associated geological formations.

Earthquake events have profound social and economic impacts on society, leading to the loss of life, and property, and damage to critical public facilities, such as buildings and transportation infrastructure. The extent of damage to public facilities resulting from earthquakes is significantly influenced by geological conditions, including local site effects, seismicity, and the topography of the area. These geological factors necessitate preparedness and effective response capabilities. The planning and development of an area should be approached with the careful consideration of various aspects. Ideally, all structures, particularly those located in earthquake-prone regions, should adhere to established standards for earthquake-resistant construction. Unfortunately, many houses and public facilities in this area have not incorporated these essential standards. As a developing regency, South Bengkulu requires sustainable disaster-focused mid-term and long-term development planning to minimize the impact on public assets and residents from the threat of earthquake hazards.

The accurate prediction of earthquake occurrences remains elusive, and earthquakes cannot be prevented

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(**Irsyam et al., 2010a; PUSGEN, 2017; PUSGEN, 2022**). The most effective approach to anticipate the impact of an earthquake is through disaster mitigation for risk reduction. Among the strategies for earthquake disaster mitigation is the implementation of a disaster-based seismic vulnerability analysis. This analysis aims to establish a specific earthquake intensity limit applicable in the study area based on a value likely to occur or be surpassed within a certain period, considering potential damage and losses in future earthquake events (**Hutapea and Mangape, 2009; Makrup, 2013**). The present study focuses on seismic vulnerability analysis utilizing parameters such as peak ground acceleration (PGA), Modified Mercalli Intensity (MMI), Seismic Vulnerability Index (K_g), shear wave velocity (V_s), and time-averaged shear wave velocity for the first 30 meters depth (V_{s30}). In the event of an earthquake, materials with high PGA, MMI, and K_g values but low V_s and V_{s30} values are prone to causing severe damage. To contribute to disaster-focused regional planning in the South Bengkulu Regency, researchers need to identify zones posing the highest risk of earthquake damage.

The presence of high seismicity in the Indian Ocean and the existence of both main and secondary faults traversing the South Bengkulu Regency area both render this area highly vulnerable, with the potential for substantial damage that could be expected during strong earthquakes in the future. As a region undergoing continuous development, the South Bengkulu Regency requires detailed information about areas prone to seismic vulnerability due to earthquakes, which is crucial for sustainable disaster-focused regional development. Given these conditions, it is imperative to estimate the level of seismic vulnerability in South Bengkulu Regency. This study is of utmost urgency, as it enables the identification and proper mapping of areas with varying levels of seismic vulnerability, particularly within the study area. The primary objectives of this study include identifying high and low seismic vulnerability areas, zonation mapping of seismic vulnerability levels, reflecting these vulnerability levels, and analysing the factors contributing to seismic vulnerability in the South Bengkulu Regency. The outcomes of this study could serve as valuable recommendations for disaster-focused regional planning, contributing to efforts aimed at anticipating and reducing disaster risks in the study area. To achieve the study's goals, various parameters such as peak ground acceleration (PGA), Modified Mercalli Intensity (MMI), Seismic Vulnerability Index (K_g), shear wave velocity (V_s), and average shear wave velocity to a depth of 30 meters (V_{s30}) were analyzed. Their impact on the level of seismic vulnerability in the South Bengkulu Regency is thoroughly estimated and presented in this paper.

2. Data and Methods

Figure 2 presents the research framework implemented in this study. This study is initiated by collecting secondary data, including the earthquake catalogue within the period of 1922 to 2022. Along with secondary data collection, the geophysical investigation of the study area is performed. In this study, the passive method uses a seismometer to measure ambient noise. From ambient noise measurement, the reliable curves and clear peaks based on **SESAME (2004)** are determined. The predominant frequency (f_0) and amplitude (A_0) are used to calculate the seismic vulnerability index (K_g). Based on the secondary data analysis, PGA distributions are presented. In this study, the Kanai model is used. Another input for PGA analysis is the natural period (T_0). Also, from PGA, the MMI level in the study area can be determined. The inversion analysis is performed to generate V_s profiles for the investigated sites. The distributions of V_s (near surface), V_{s5}, V_{s10}, V_{s15}, V_{s20}, V_{s25}, and V_{s30} are presented. In general, there are three important stages in this study, i.e. the stage of data acquisition and collection, the stage of data processing, and the stage of data interpretation and analysis. These stages are detailed in the next sub-sections.

2.1. Stages of Data Acquisition and Collection

Secondary data collection serves as input for obtaining Peak Ground Acceleration (PGA) values. Earthquake catalog data, obtained from reputable agencies such as the US Geological Survey (https://earthquake.usgs.gov/earthquakes/search/) and the International Seismological Center (http://www.isc.ac.uk/iscbulletin/search/catalogue/), form the primary sources for this secondary data. The earthquake catalog data include parameters such as magnitude, coordinates of the earthquake epicenter, and earthquake depth, covering the period from 1922 to 2022. The chosen magnitude scale focuses on large magnitudes (≥ 5) and shallow earthquake depths (≤ 50 km), under the assumption that destructive earthquakes tend to exhibit both large magnitudes and shallow depths. During the field investigation phase, the Horizontal to Vertical Spectral Ratio (HVSR) technique was employed to collect microtremor data. The HVSR technique helps identify resonance responses related to the Seismic Vulnerability Index (K_g) in sedimentary basins (**Nakamura et al., 2003; Nakamura, 2008; Daryono, 2011**). Measurement points using the HVSR method were adapted to field conditions, selecting data points across various lithologies concerning the regional geological map of the Manna Sheet in South Bengkulu. **Bonnefoy-Claudet et al. (2006)** mentioned that determining the predominant period could be performed by the HVSR technique, but estimating the clear peak of H/V could be difficult. In addition, external effects, such as human noises, environmental settings, and other surficial sources, usually influence the measurement results. This may be the main limitation of ambient noise measurement under the HVSR technique. Nevertheless, the effort to minimise those external effects could be applied to ensure a better measurement quality.

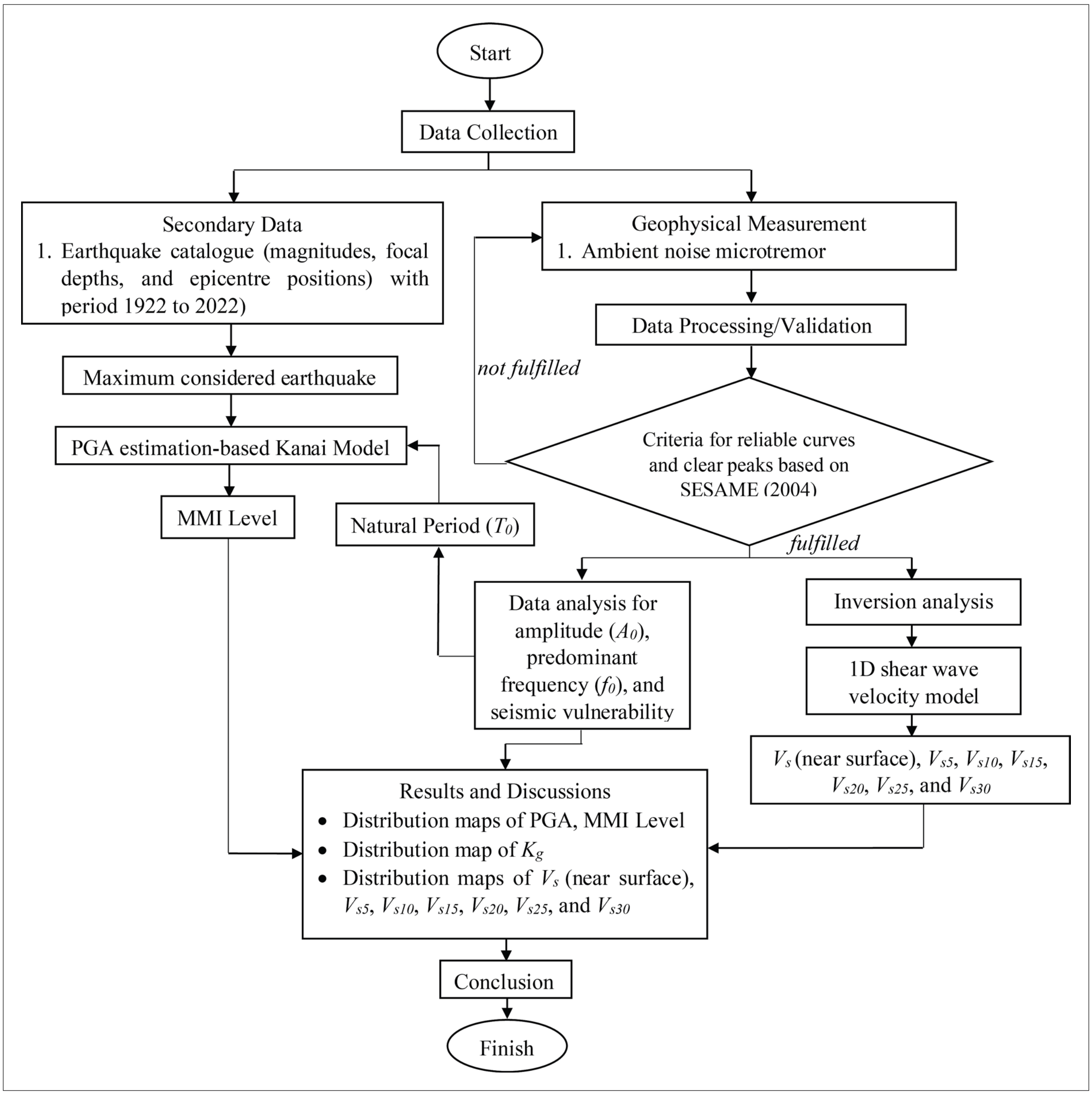

Figure 2: Research framework

The further analysis of HVSR results is to depict the ground profile. However, to reduce the uncertainty effect, a priori knowledge based on site investigation data should be provided as a starting guess model, as suggested by **Mase et al. (2021a, 2023)**. In line with the benefit of the method, the passive method using a seismometer to measure ambient noise is still widely used in engineering practice.

Measurements were conducted using the portable short-period Broadband Seismometer survey equipment by PASI Mod. Gemini 2 s.n. 14065 (triaxial geophone). The Site Effects Assessment using Ambient Excitation (SESAME) standard is being employed for microtremor data collection. According to **SESAME (2004)**, if most research sites are relatively rare, then data collection may require an extended duration but can still yield useful results. Hence, field data collection for 30 minutes at all research locations was assumed to be sufficient, given that the obtained data during this time were representative and of good quality.

2.2. Stages of Data Processing

After collecting secondary data from various relevant sources and conducting field surveys, the data processing stages were initiated. At the coordinate points of the research location, the distance from the earthquake epicenter to the measurement point (epicentral distance) was measured using the method described by **Bullen (1980)**:

$$\cos\Delta = \left(a_e a_s + b_e b_s + c_e c_s\right) \tag{1}$$

$$\tan\theta' = 0.99\tan\theta \tag{2}$$

Where:

$a = \cos\theta' \cos\lambda$,

$b = \cos\theta' \sin\lambda$,

$c = \sin\theta'$,

θ = geographic latitude,

θ' = geocentric latitude,

λ = longitude,

subscript e = for epicenter,

subscript s = for the station (measurement point).

Seismic records furnish crucial information about earthquakes, encompassing details such as the epicenter's latitude and longitude, along with the earthquake's magnitude and depth. This information undergoes processing to derive a Peak Ground Acceleration (PGA) value for consistency in earthquake catalogs. The data sourced from the earthquake catalogs of the US Geological Survey (USGS) and the International Seismological Center (ISC) still exhibit variability in magnitude. Consequently, a conversion to a consistent magnitude scale is imperative before further processing. The non-uniform magnitude scale is transformed into moment magnitude (Mw) units, which offer a standardized measure of earthquake strength (**Hanks and Kanamori, 1979**). The conversion from various magnitude scales to moment magnitude units is performed using the method outlined by **Asrurifak (2010)**:

$$M_w = 0.143M_s^2 - 1.051M_s + 7.285 \quad (3)$$

$$M_w = 0.114m_b^2 - 0.55m_b + 5.560 \quad (4)$$

$$M_w = 0.787M_E + 1.537 \quad (5)$$

$$m_b = 0.125M_L^2 - 0.389M_L + 3.513 \quad (6)$$

$$M_L = 0.717M_D + 1.003 \quad (7)$$

$$M_w = \left(\frac{2}{3}\right)\log M_o - 1.07 \quad (8)$$

Where:

M_w is the moment magnitude scale,

m_s is the surface wave magnitude scale,

m_b is the body magnitude scale (body wave effect),

M_E is the energy magnitude scale,

M_L is the local magnitude scale from Richter,

M_D is the duration magnitude scale,

M_o is the seismic moment.

The distance from the measurement point to the focus of the earthquake is obtained from (**Bullen, 1980**):

$$R = \sqrt{\Delta^2 + h^2} \quad (9)$$

Where:

Δ is the epicentral distance,

h is the depth at which the quake fell.

The PGA value can be obtained through the Kanai formulation (**Douglas, 2022**):

$$\alpha = \frac{5}{\sqrt{T_G}} 10^{0.61M_w - 1.660.61M_w - 1.66\log 10R - \frac{3.60}{R}\log R + 0.167 - \frac{1.83}{R}} \quad (10)$$

Where:

α is the PGA (gal),

R is the shortest distance from the location to the focus of the earthquake (km),

M_w is the moment magnitude scale,

T_G represents the predominant period of ground motion at the point (or sites) of observation.

Then there's the MMI value, which can be calculated by relating the PGA value to the MMI value at each specific position. **Wald et al. (1999)** provide the following formula for converting between PGA and the Modified Mercalli Intensity (I_{mm}) scale:

$$I_{mm} = 3.66\log(\alpha) - 1.66 \quad (11)$$

The HVSR approach continues to provide microtremor data in the time domain, preserving all three components: the horizontal (North-South/NS and East-West/EW) and vertical (Up-Down/UD) components. Manual signal selection is employed to obtain the most stationary signal. During the windowing process, the stationary signal is partitioned into multiple windows, with the window width determined according to the SESAME European Research Project guidelines **(SESAME, 2004)**. The Fast Fourier Transform (FFT) is subsequently applied for frequency domain conversion. The spectra of the NS and EW components are then combined to derive the ratio of HVSR values, representing the spectrum of the horizontal component to the vertical component. To ensure the quality of the resulting data, smoothing is applied using the equation proposed by **Konno and Ohmachi (1988)** with a selected available bandwidth. Subsequent data processing involves HVSR curve analysis. The output of the HVSR method includes the soil predominant frequency (f_0) and amplification value (A_0) at the study site. The f_0 value is further converted into the dominant soil period (T_G) as input for **Equation 10**.

Soil predominant frequency values (f_0) and amplification (A_0) are also used as input parameters to obtain K_g values through the equation (**Nakamura et al., 2003; Nakamura, 2008**):

$$K_g = \left(\frac{{A_0}^2}{f_0}\right) \quad (12)$$

The Win-MASW 5.2 HVSR (**PASI, 2017**) software was utilized to analyze the waveform spectrum of recorded microtremor data. This program allows for a clear distinction between natural vibrations and transient vibrations in both the horizontal components (North-South/NS and East-West/EW) and the vertical component (Up-Down/UD), facilitating the selection of data. Additionally, the program provides insight into the reliability of the data and the distinct peak Horizontal-to-Vertical Ratio (HVSR) at each research location. By SESAME guidelines (**SESAME, 2004**), data is considered acceptable (reliable) if the HVSR curve meets the following criteria:

$$f_0 > 10 / I_w \quad (13)$$

$$n_c(f_0) > 200 \quad (14)$$

$$\sigma_A(f) < 2 \text{ for } 0.5 f_0 < f < 2 f_0 \text{ if } f_0 > 0.5 Hz \text{ or} \quad (15)$$

$$\sigma_A(f) > 2 \text{ for } 0.5 f_0 < f < 2 f_0 \text{ if } f_0 < 0.5 Hz \quad (16)$$

Where:

f_0 is the predominant frequency (peak frequency, HVSR),

I_w is the window length,

$n_c = I_w . n_w . f_0$ is the total number of cycles that have significance,

n_w is how many windows were chosen for the average HVSR curve.,

σ_A is the standard deviation.

After obtaining f_0 and A_0 values that adhere to SESAME criteria, the inversion process is initiated using the Hv-Inv software. This software operates by iteratively adjusting the initial model to align with the Horizontal-to-Vertical Spectral Ratio (HVSR) curve obtained from field measurements. The iterative process continues until a final model is achieved, demonstrating a match between field data and model data. The initial model includes parameters such as layer thickness (*h*), a range of shear wave velocity values (V_s), a range of compression wave velocity values (V_p), a range of density (ρ), and a range of Poisson ratio values (*n*). Achieving a match between field data and model data (minimum misfit) involves employing a random analysis using the Monte Carlo method through an iterative process. The iteration process is halted once the smallest misfit value is obtained. Upon reaching the minimum misfit value, the subsequent step involves refining the parameter values to obtain V_s and V_{s30}.

2.3. Stages of Data Interpretation and Analysis

The analysis and interpretation of data obtained from contour maps illustrating suspected seismic vulnerability levels due to earthquakes are conducted based on the values of PGA, MMI, K_g, V_s, and V_{s30}. Utilizing these parameters, the contour map depicts the potential severity of seismic vulnerability, enabling the identification of areas within South Bengkulu Regency at risk of earthquake impact. Regions exhibiting high values for PGA, MMI, and K_g, coupled with low values for V_s and V_{s30}, are deemed to possess a heightened risk of earthquakes. This seismic vulnerability map serves as a valuable consideration in the planning of future disaster-focused sustainable regional development in the study area. The aim is to utilize this map to mitigate the risk of disasters arising from the threat of earthquake hazards.

3. Results and Discussion

This section presents the data compilation used in this study and the vulnerability level. The discussion and comparison to the previous studies are also presented. Secondary data collection from earthquake catalogs was sourced from the US Geological Survey (USGS) and the International Seismological Center (ISC) covering a span of years from 1922 to 2022. The catalog comprises 909 earthquake events with a magnitude of ≥ 5 and a depth of ≤ 50 km, occurring within the coordinates of -1.63° S to -6.98° S and +99.82° E to +106.27° E. The selection criteria for magnitude, earthquake depth, and coordinates are based on the occurrence of large earthquakes, shallow earthquake depths, and locations that have the potential to impact disaster risk in the study area. The catalog data includes earthquake parameters such as magnitude, depth, and epicenter. The distribution of earthquake epicenters around the study area is showed in **Figure 3**.

In **Figure 3**, spanning a period of 100 years (1922–2022), the seismicity level of earthquakes around South Bengkulu Regency appears more pronounced than in the surrounding areas. This phenomenon is attributed to the magnitude of tectonic energy and the strain rate in the southern part of Sumatra Island, including the South Bengkulu area in Bengkulu Province. This heightened seismic activity is triggered by the movement of the sliding slab, facilitating fault occurrences (**Megawati et al., 2005; Murjaya, 2011; PUSGEN, 2017; PUSGEN, 2022**). In addition to the secondary data obtained from the earthquake catalog, microtremor data, considered primary data representing the dominant period of the soil, is utilized as input for determining the Peak Ground Acceleration (PGA) value using the Kanai formulation in **Equation 10** (**Douglas, 2022**). Microtremor data is evenly distributed throughout the study area, with a total of 104 measurement points (as shown in **Figure 1**). The output from the microtremor data includes predominant frequency values and soil amplification factors at each measurement point. An example of the output illustrating the predominant frequency value and ground amplification factor is presented in **Figure 4**. The predominant frequency value (f_0) and soil amplification factor (A_0) have undergone reliability testing, meeting the requirements outlined in **SESAME (2004)**. These values are also used as input for calculating the seismic vulnerability index (K_g) as specified in **Equation 12**. **Figure 4** illustrates the distribution of PGA values in the South Bengkulu area.

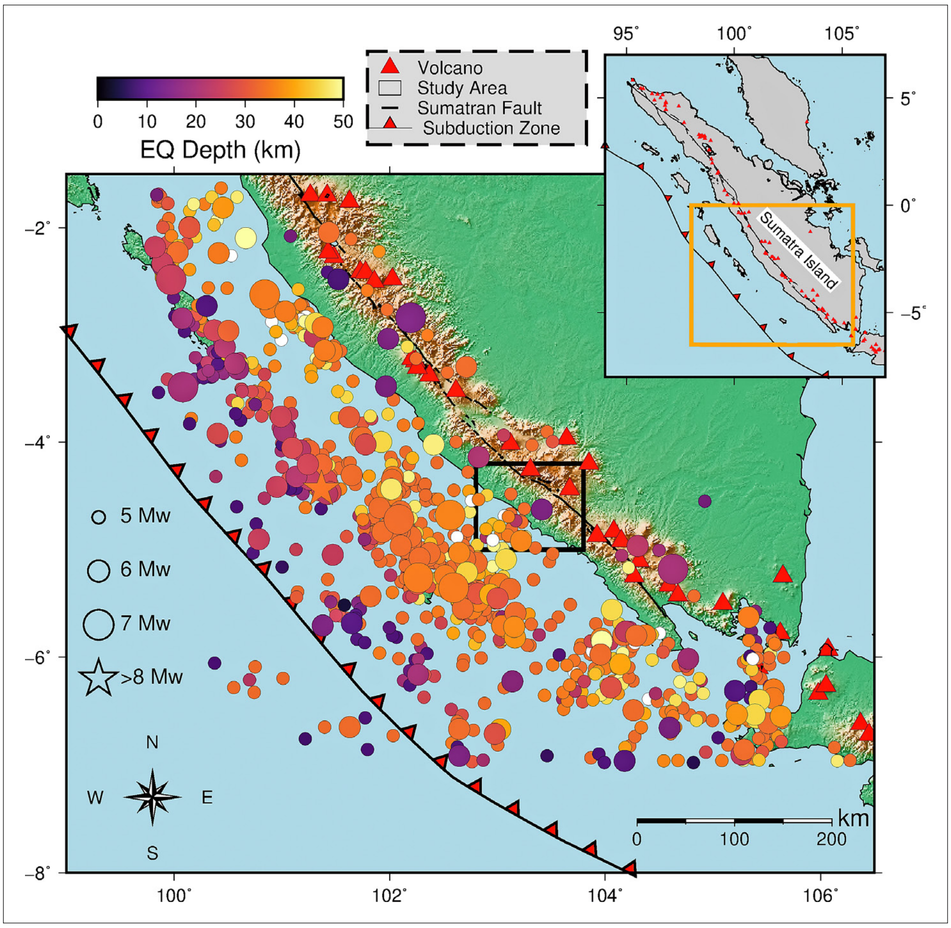

Figure 3: The earthquake event distribution around the study area

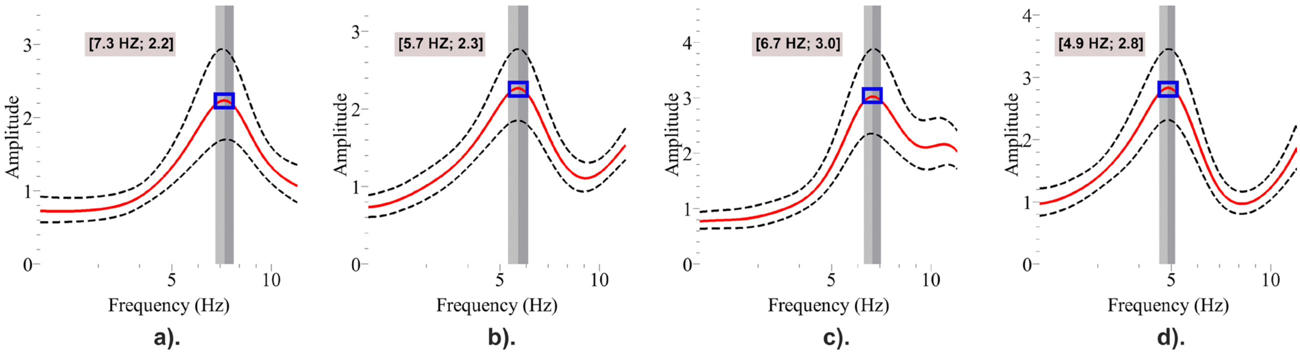

Figure 4: Examples of HVSR processing results are the values of predominant frequency (f_o) and soil amplification factor (A_o). (a) at the T3 measurement point with f_o = 7.3 Hz and A_o = 2.2, (b) at the measurement point T11 with f_o = 5.7 Hz and A_o = 2.3, (c) at the measurement point T10 with f_o = 6.7 Hz and A_o = 3.0, and (d) at the measurement point T15 with f_o = 4.9 Hz and A_o = 2.8

The obtained Peak Ground Acceleration (PGA) values in the field ranged between 0.19 g and 0.54 g, as shown in **Figure 5**. According to BNPB (2012) standards, these PGA values fall within the low to moderate category. PGA hazard categories are classified as low PGA, moderate PGA, and high PGA. Specifically, PGA is considered as low if PGA < 0.26 g, as moderate PGA if 0.26 ≤ PGA ≤ 0.7g, and as high if PGA > 0.7g. It is anticipated that the PGA values in the study area are significantly influenced by site characteristics. Regions with high seismic vulnerability are those exhibiting elevated PGA values, and vice versa. The spatial distribution of PGA values in this research area indicates that, generally, high PGA values are prevalent in the southwest and northeast, while low PGA values are distributed from the southeast to the northwest. **Figure 4** also shows that the dominant PGA in the study area ranges from 0.190 to 0.410g. **Zera et al. (2017)** conducted a study of the Three Peak Ground Acceleration Models in Bengkulu Province, Indonesia, using a first-generation

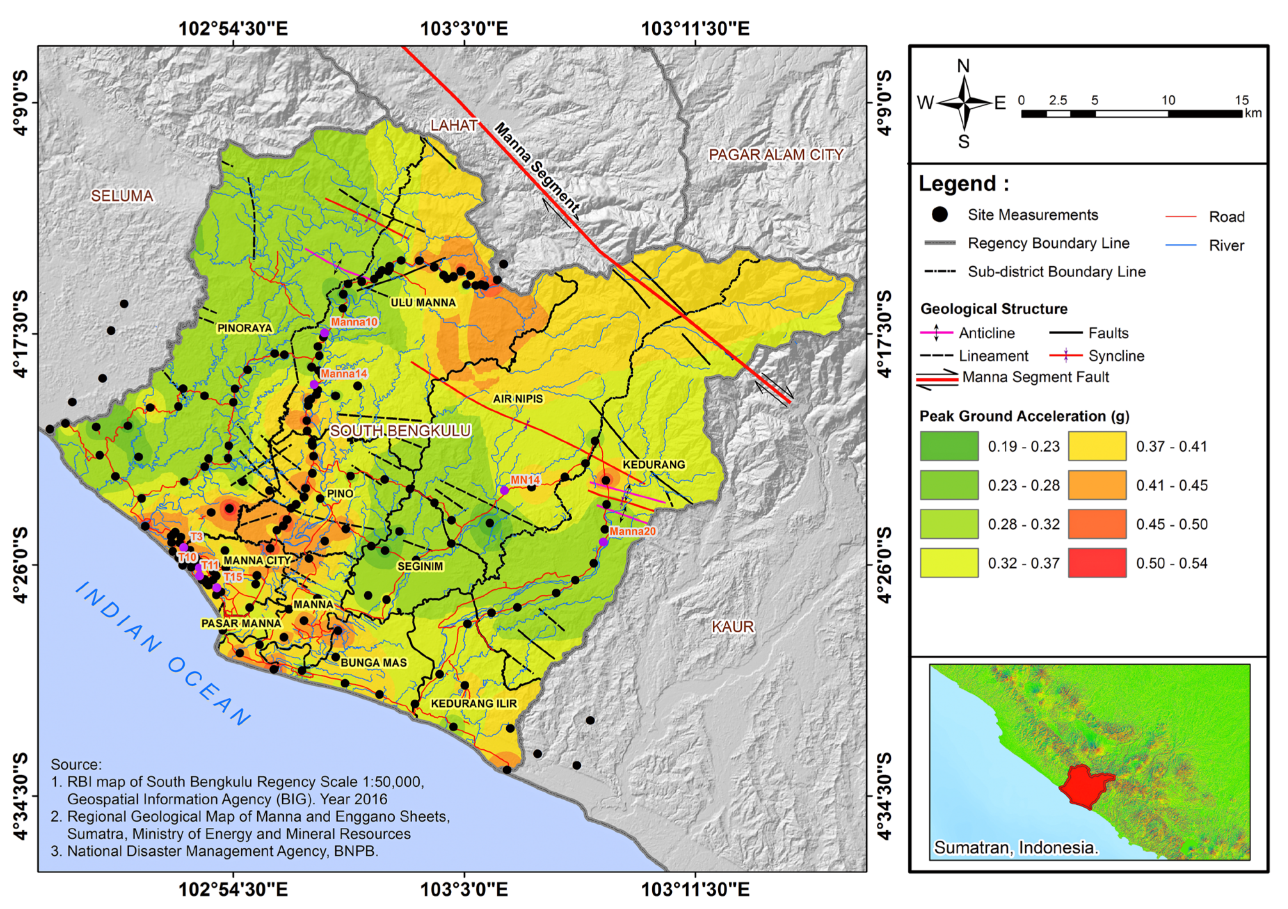

Figure 5: A representation of the PGA values obtained in the study area

attenuation model, such as **Esteva (1970)**, **Patwardhan et al. (1980)**, and **Crouse (1991)**. According to **Zera et al. (2017)**, PGA in the study area is observed to vary from 0.276 to 0.410g. The models considered by **Zera et al. (2017)** only include the main factors influencing earthquakes, such as earthquake magnitude, earthquake source distance, and focal depth. Other parameters such as earthquake mechanisms, site condition, and so on are not considered the first generation of the attenuation model. **Puteri et al. (2019)** performed the analysis of PGA using Probabilistic Seismic Hazard Analysis in Bengkulu Province using the earthquake catalogue from 1900 to 2017. **Puteri et al. (2019)** also mentioned that the PGA of South Bengkulu Regency is observed to vary from 0.310 to 0.380g. According to a study conducted by **Irsyam et al. (2010b)**, based on probabilistic seismic hazard analysis (PSHA), PGA in the study area generally ranges from 0.300 to 0.500g for a 10% Probability of Exceedance in 50 years. The lower boundary of PGA from this study is generally lower than **Irsyam et al. (2010b)**. However, the upper boundary of PGA from this study is still within the range of **Irsyam et al. (2010b)**. It should be noted that in PSHA, the probabilities of magnitude, magnitudes, and earthquake mechanisms are also considered. Under the aggregation method, the most credible earthquake with the most potential magnitude and distance to produce the most significant damage is determined. Therefore, the results could be higher. Overall, the results of this study are generally consistent with the previous studies.

After determining PGA values, a correlation between each PGA and the Modified Mercalli Intensity (MMI) can be calculated for each research site using the steps outlined in **Equation 11**. **Figure 6** depicts a map representing the distribution of MMI in the South Bengkulu Regency. MMI values in the research area are predominantly within the VII–VIII scale, while the VI scale is notably present in specific sites, particularly along the east and west of the geographic centre of the area. According to **Wood and Ratliff (2011)**, the social impacts experienced at these MMI scales range from vibrations felt by everyone, light damage to houses with good construction, to cracks in strong buildings, and walls separating from the house frame.

Figure 7 represents the distribution of seismic vulnerability index values (K_g) throughout the area that was under investigation. K_g values obtained in the field ranged from 0.02 to 6.78. The value of K_g at the research location belongs to the low to moderate category. Seismic vulnerability is determined by its vulnerability index (K_g). The K_g value is considered large if the seismic vulnerability index is ≥ 8.5 which has the potential to

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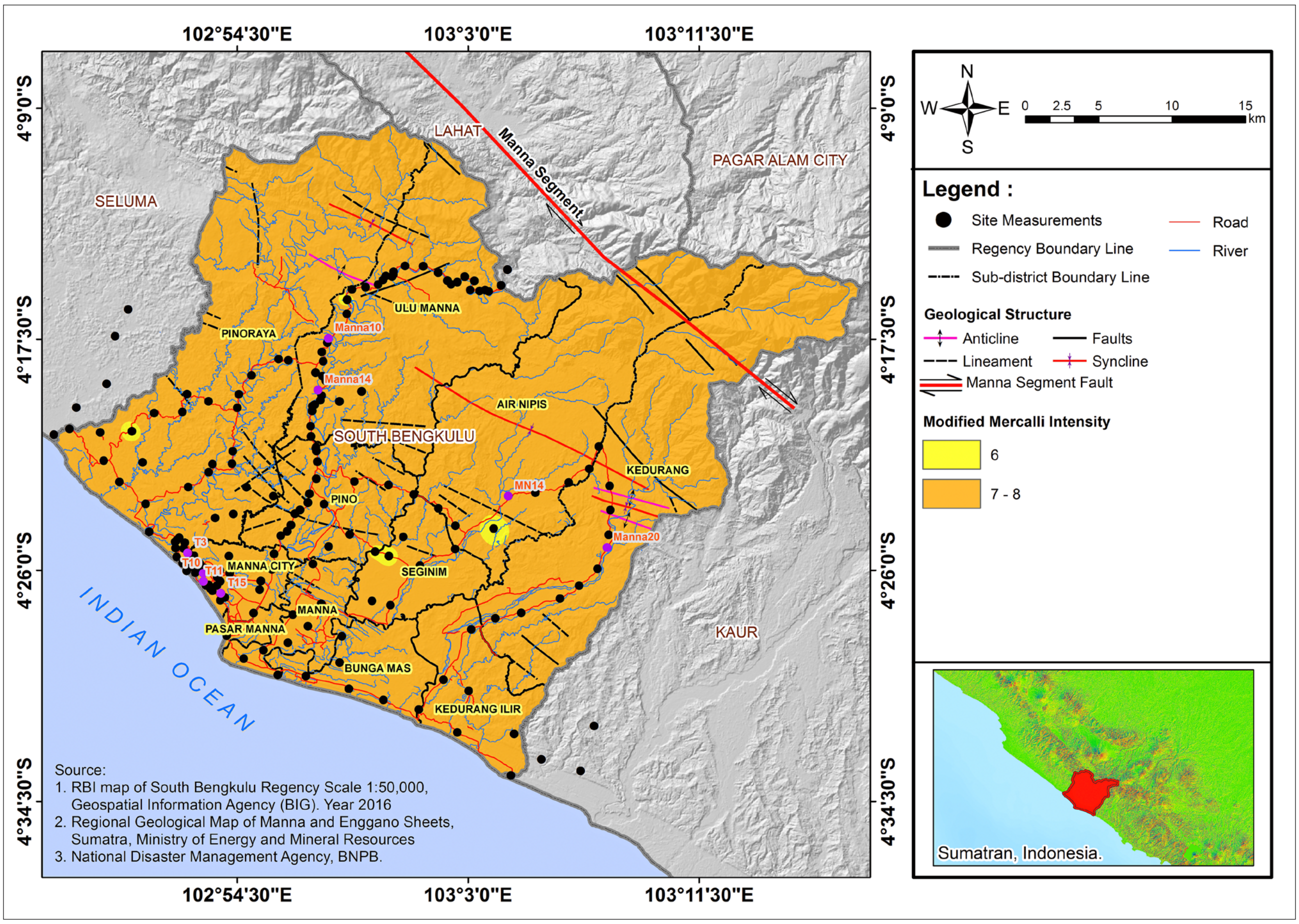

Figure 6: A representation of the MMI values obtained in the study area

experience deformation in the event of an earthquake (**Daryono, 2011; Farid, 2014; Hadi, 2019**). In terms of geophysical aspects, the study area tends to have relatively low-moderate seismic risk. However, the maximum seismic vulnerability zone is also depicted in the small part of the southern and middle parts of the study area. Several studies conducted by **Mase et al. (2021a, 2021b)** also mentioned that a higher seismic vulnerability index reflects the potential seismic damage in an area, especially in Bengkulu city, (the neighbouring city to the study area). The combination between a high value of amplitude and a low predominant period could result in a large seismic vulnerability. A large amplitude could reflect the distribution of high impedance contrast between rock and sediment, whereas a low predominant period could reflect the uniform thick sediment thickness. Therefore, the mitigation plan in terms of specific local seismic design should be proposed to help spatial plan development (**Mase, 2022**).

Daryono (2011) reports a correlation between seismic vulnerability and the ratio of building damage, indicating that sites more susceptible to earthquakes generally experience more severe damage, and vice versa. This observation aligns with specific earthquake events such as the May 27, 2006 earthquake in Yogyakarta and the September 19, 1985 earthquake in Michoacan, Mexico City. In these instances, severe damage was concentrated in the graben area and thick sediment deposits with a Seismic Vulnerability Index (K_g) value of ≥ 8.5 (**Pontoise and Monfret, 2004; Daryono, 2011**). In contrast, **Farid (2014)** highlights that a K_g value of 16.1 can lead to rock deformation in soft rock coastal areas, causing issues like abrasion, erosion, landslides, and rockfalls. Referencing the earthquake on June 4, 2000, in Bengkulu Province, particularly the South Bengkulu Regency area near the epicenter, the damage caused was relatively lower than in Bengkulu city, where the epicenter was farther away. This difference is attributed to the research area's low seismic hazard index. The subsequent step in the study involves establishing a value for shear wave velocity, denoted as V_s. Employing an inversion technique, shear wave velocity values were computed from microtremor data. The result of this inversion process provided shear wave velocity values for each rock layer thickness. Subsequently, the average velocity of shear waves at a depth of 30 meters, referred to as V_{s30}, was calculated. **Figure 8** displays the shear wave velocity values for each rock layer thickness (V_s) and V_{s30} measured at various study sites.

In **Figure 8**, it is evident that the V_s values generally increase with depth, indicating a denser composition deeper into the rock. The obtained V_s values in the field

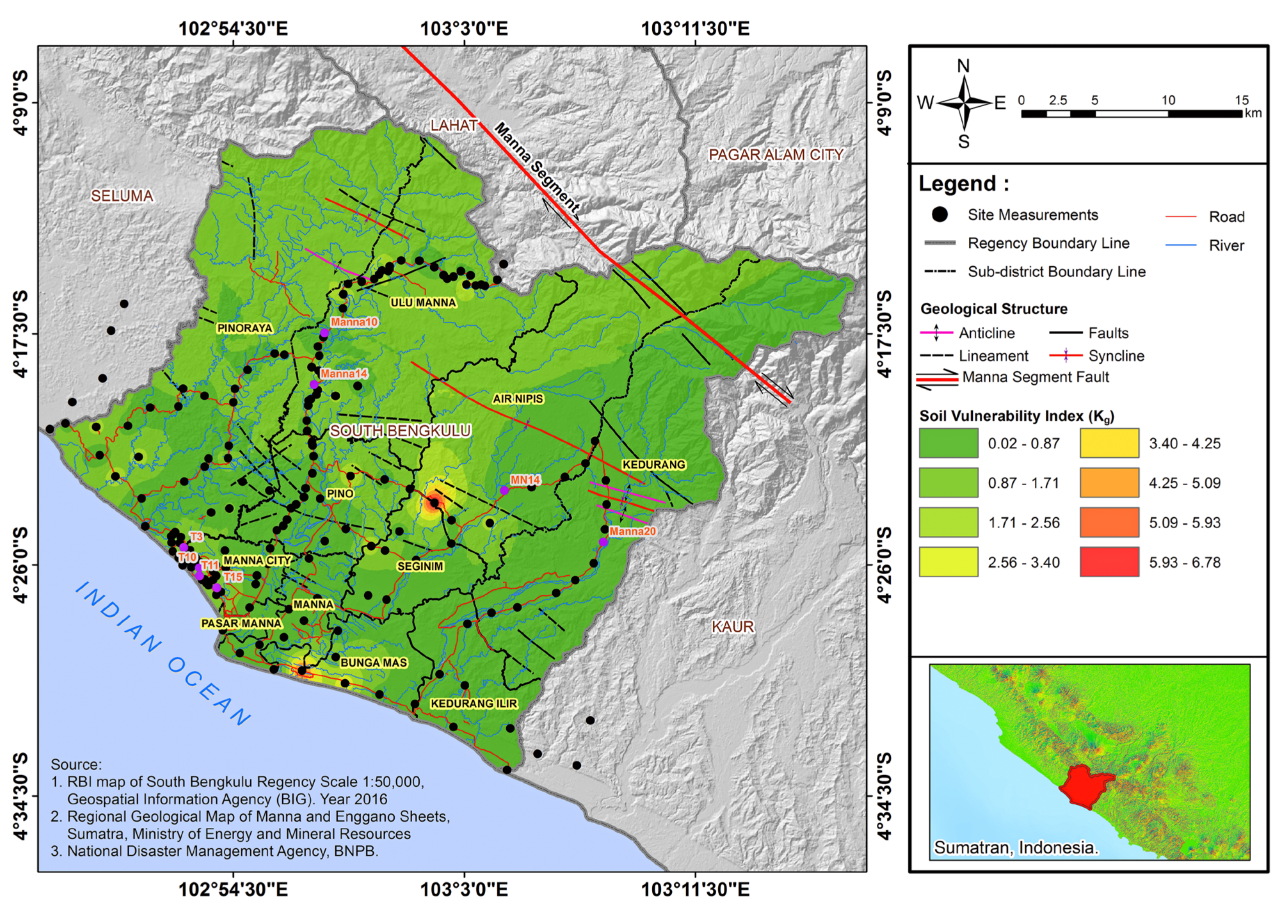

Figure 7: Representation of the seismic vulnerability index (K_g) values obtained in the study area

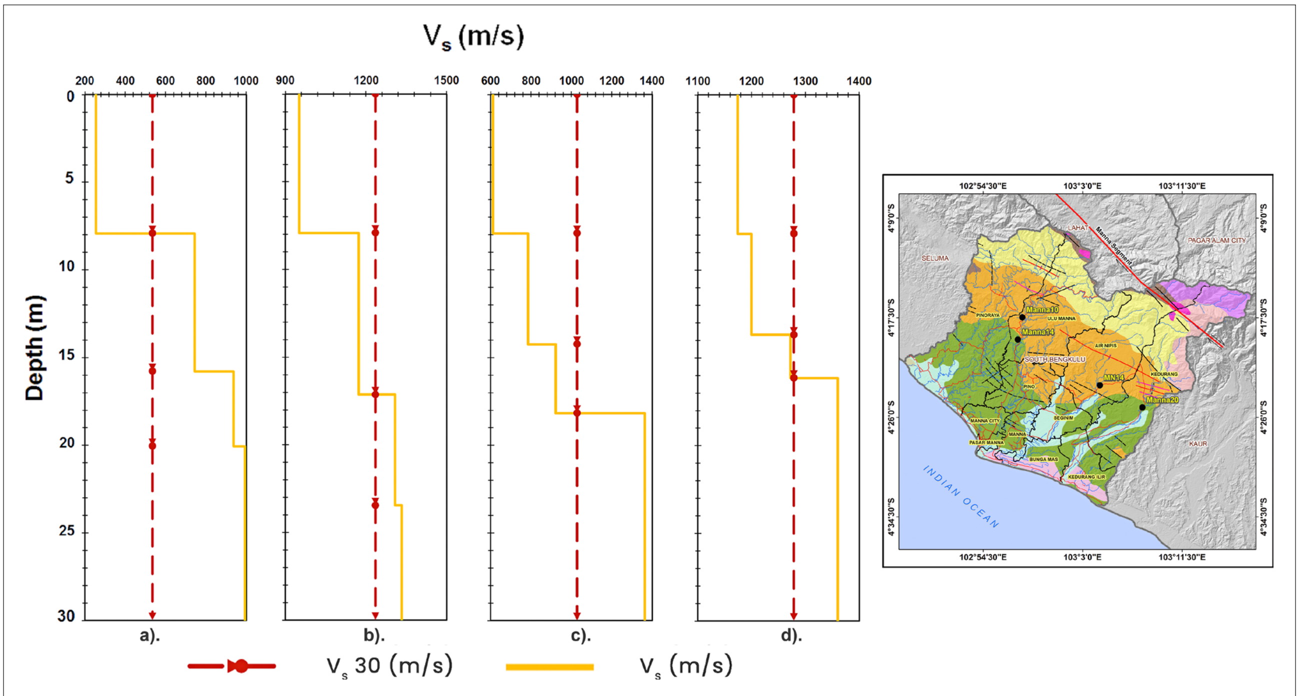

Figure 8: Example of V_s values in the thickness of each rock layer and V_{s30} at several research locations: (a) Mn 14 location, (b) Manna 20 location, (c) Manna 10 location, and (d) Manna 14 location

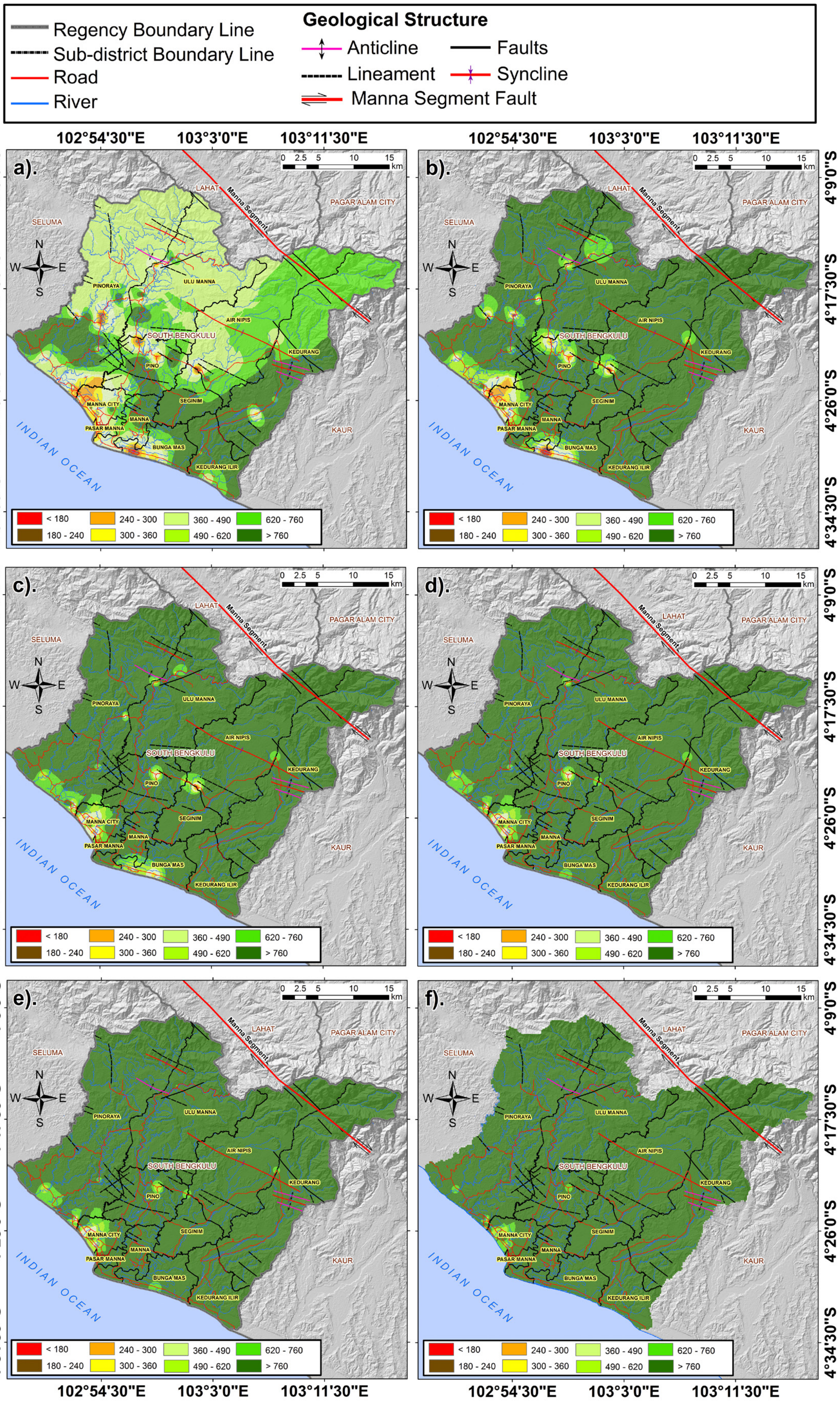

Figure 9: Distribution of V_s values for several layer thicknesses: a). $V_{s\ near\ surface}$, b) V_{s5}, c). V_{s10}, d). V_{s15}, e). V_{s20}, and f). V_{s25}

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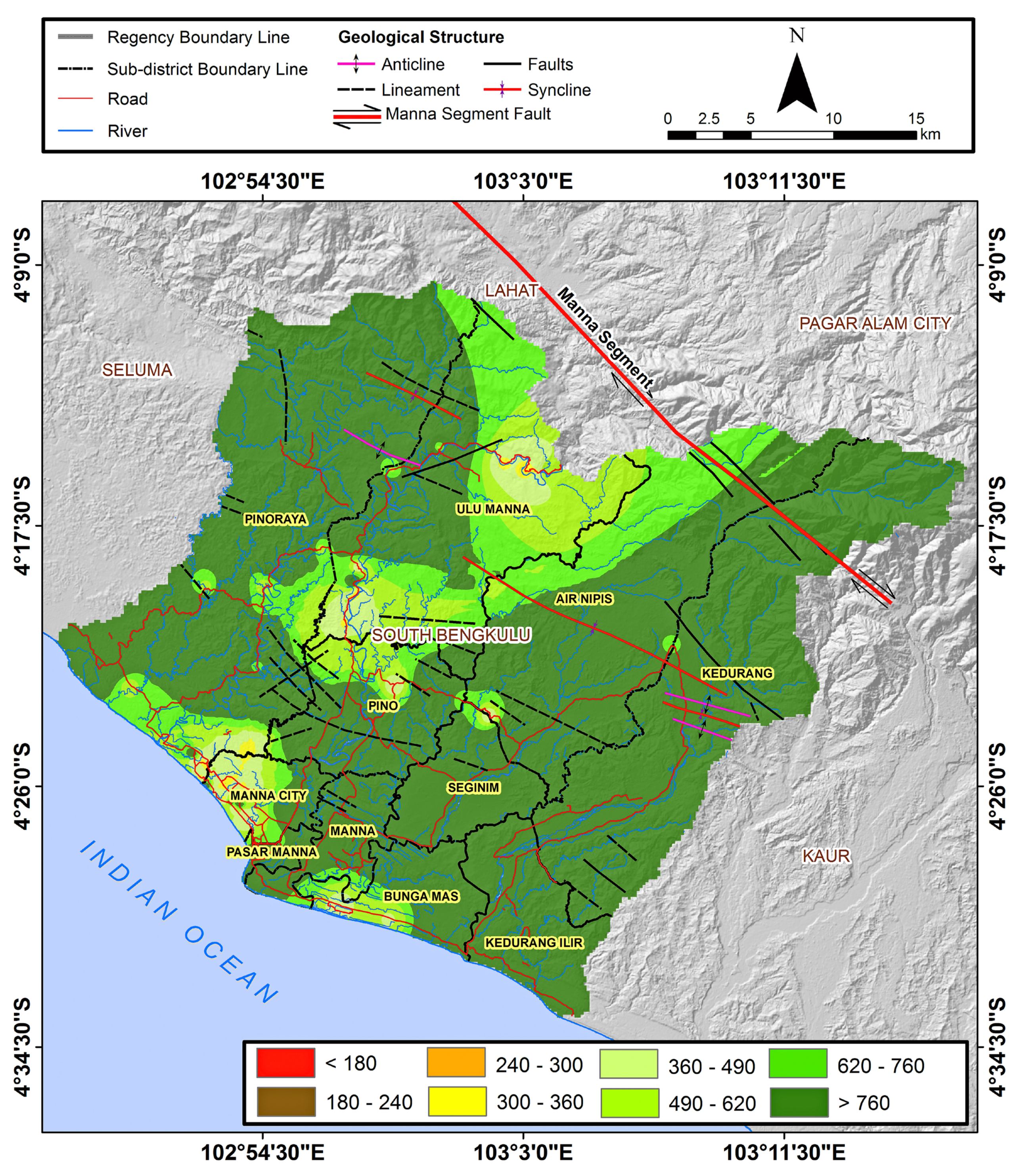

Figure 10: Distribution of V_{s30} values in the study area (**Hadi et al., 2023**)

range between 165 m/s and 3568 m/s. According to **SNI (2019)**, V_s values less than 175 m/s classify as soft soil, V_s values between 175 m/s and 350 m/s as medium soil, V_s values between 350 m/s and 750 m/s as stiff soil and soft rocks, V_s values between 750 m/s and 1500 m/s as rocks, and V_s values exceeding 1500 m/s as hard rocks. On the other hand, following **BSSC (2020)**, V_s values less than 152 m/s are categorized as very loose sand or soft clay, V_s values between 152 m/s and 213 m/s are categorized as loose sand or medium stiff clay, V_s values between 213 m/s and 305 m/s as medium dense sand or stiff clay, V_s values between 305 m/s and 442 m/s as dense sand or very stiff clay, V_s values between 442 m/s and 640 m/s as very dense sand or hard clay, V_s values between 640 m/s and 914 m/s as soft rock, V_s values between 914 m/s and 1524 m/s as medium-hard rock and

V_s values exceeding 1524 m/s as hard rock. In this study, V_s values at specific depths were provided for V_s near the surface, V_{s5}, V_{s10}, V_{s15}, V_{s20}, and V_{s25}. The distribution of V_s near the surface, V_{s5}, V_{s10}, V_{s15}, V_{s20}, and V_{s25} is showed in **Figure 8**.

The classification of V_s values follows **Allen and Wald's (2009)** eight-class division. Low V_s values correspond to areas with high seismic vulnerability, while high V_s values correspond to areas with low seismic vulnerability. As depicted in **Figure 9**, the V_s near-surface values reveal several areas with relatively high seismic vulnerability, particularly in the southwest and northeast compared to the surrounding regions. However, these areas do not fall into the soft soil category. At greater depths, namely V_{s5}, V_{s10}, V_{s15}, V_{s20}, and V_{s25}, the values increase with depth, indicating denser rock formations. The subsequent analysis focuses on V_{s30}. This analysis is crucial because, as noted by **Wangsadinata (2006)**, earthquake wave magnification is limited to rock layers up to 30 m in depth. V_{s30} is a geotechnical parameter commonly employed in seismic wave analysis. **Figure 9** illustrates the distribution of V_{s30} values across South Bengkulu Regency.

In **Figure 10**, the V_{s30} value in the South Bengkulu area falls into the high category, specifically more than 300 m/s, indicating a high level of rock solidity in the study area. Referring to **BSSC (2020)**, the study area is predominantly characterized by very dense sand or hard clay, and soft rock, with some locations showing dense sand or very stiff clay and medium dense sand or stiff clay, particularly in the southwest and northeast directions. Based on the rock site class, this research area comprises only very dense soil (SC) and rock (SB) (**Hadi et al., 2023**). To facilitate the sustainable development of disaster-resilient areas, it is crucial to avoid locations with a high potential for earthquake threats, construct facilities and infrastructure that adhere to earthquake standards, enhance community and government capacity through sustained mitigation and preparedness efforts, and establish integrated and systematic early warning systems (**BNPB, 2012; Hadi et al., 2021a**).

4. Conclusions

This paper presents zonation of seismic vulnerability levels in South Bengkulu Regency for disaster-based regional planning. The geophysical investigation using microtremor measurement to depict seismic vulnerability and site classification distribution are conducted. Several concluding remarks based on this study can be drawn:

- Based on the parameters such as PGA, Seismic Vulnerability Index (K_g) being relatively low, and the values of V_s, V_{s30}, and MMI scale being quite high, the overall level of seismic vulnerability in the South Bengkulu Regency area is categorized as low. However, there are specific areas with notably high seismic vulnerability, particularly in the southwestern and northeastern zones. Therefore, it should be noted that despite this low level of seismicity occurrence in this area, the area is still prone to significant damage in case of triggered seismicity even at a low level due to the nature of rock materials and the brittleness of the rocks in the area. Further investigation will be performed and presented in the future.
- The factors contributing to this heightened vulnerability are attributed to large PGA values. Despite this, the South Bengkulu area, in general, exhibits a high level of soil density, which serves to minimize the risk posed by earthquake threats. As a recommendation for future research, it is advisable to incorporate subsurface borehole data to further investigate and strengthen the understanding of the physical parameters.
- To depict a more accurate prediction in terms of the soil profile and shear wave velocity distribution, other geotechnical investigations, such as boring, standard penetration tests (SPT), and seismic downhole tests can be performed. Those site investigations can give a better understanding in terms of soil resistance so that it can be useful for structural design and spatial development based on hazard mitigation. It will be presented in future studies.

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SAŽETAK

Zoniranje stupnja seizmičke ranjivosti u pokrajini Južni Bengkulu u svrhu regionalnoga smanjenja rizika od katastrofa

Točno predviđanje i mjere ublažavanja od potresa i dalje su izazov. Posljedično, primarni pristup ublažavanju posljedica od potresa temelji se na provođenju mjera za smanjenje rizika od katastrofa. Jedna važna strategija uključuje provođenje analiza seizmičke ranjivosti na temelju scenarija katastrofa. U okviru ovoga istraživanja cilj je bio identificirati i kartirati područja s različitim razinama seizmičke ranjivosti analizirajući faktore koji pridonose ranjivosti u pokrajini Južni Bengkulu. Prikupljeni su sekundarni podatci koji uključuju vršne vrijednosti ubrzanja tla (PGA), zajedno s podatcima o mikrotremoru dobivenim metodom omjera horizontalnoga i vertikalnoga spektra (HVSR). Snimljeni podatci mikrotremora služe kao ulazni parametri za PGA, modificirani Mercallijev intenzitet (MMI), indeks seizmičke ranjivosti (K_g), brzinu posmičnoga vala (V_s) i prosječnu vremensku brzinu posmičnoga vala za prvih 30 m dubine (V_{s30} vrijednosti). Rezultati su pokazali da se seizmička ranjivost u pokrajini Južni Bengkulu može generalno kategorizirati kao niska. Međutim, određena područja, posebno u jugozapadnome i sjeveroistočnome dijelu, pokazuju relativno više razine ranjivosti. Povišena ranjivost u tim područjima pripisuje se povišenim PGA vrijednostima, unatoč općenito visokoj gustoći tla u regiji, koja djeluje kao faktor ublažavanja ranjivosti od potresa.

Ključne riječi:
potres, rizik od katastrofe, seizmička ranjivost, Južni Bengkulu, Indonezija

Author's contribution

Arif Ismul Hadi (1) (PhD, Associate Professor, Seismic Hazard Analysis) provided analysis and interpretation of seismic vulnerability due to earthquakes. **M. Farid (2)** (PhD, Full Professor, Disaster Mitigation) analyzed the results of seismic vulnerability modelling. **Lindung Zalbuin Mase (3)** (PhD, Associate Professor, Civil Engineering) provided a seismic vulnerability level map and its interpretation. **Refrizon (4)** (Associate Professor, Geophysics) provided field data analysis. **Shela Basaria Purba (5)** (Student, Geophysics) conducted field data acquisition and collection. **Darmawan Ikhlas Fadli (6)** (Researcher, Geophysics) created digital geological maps. **Erlan Sumanjaya (7)** (Lecturer, Geodesy) provided an analysis of geological map results and seismic vulnerability level maps.