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Original research article

Seismic microzonation and geotechnical characteristics of Manna City, South Bengkulu

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A B S T R A C T

As one of the disaster-prone areas in Manna, this city is prone to disasters. This study aims to evaluate the potential risk of earthquakes in Manna through a seismic microzonation approach. Using amplification factor and dominant frequency data, this study produced a microzonation map showing areas with a higher risk of earthquake damage. The methods applied in this study include the Horizontal-to-Vertical Spectral Ratio (HVSR) and Multichannel Analysis of Surface Waves (MASW), which enable analysis of soil properties and their influence on earthquake vibration amplification. The study results reveal that areas with soft soil and high amplification, such as Pasar Manna and Pino Raya, are at higher risk of significant damage during an earthquake. Based on these findings, we recommend mitigation measures such as spatial planning that considers seismic risk, the implementation of earthquake-resistant construction, and enhancing community preparedness. By integrating these microzonation results into development policies and disaster mitigation strategies, it is hoped that the city of Manna can reduce the potential damage caused by earthquakes.

1. Introduction

This study aims to assess the potential risk of earthquakes in Manna City, South Bengkulu Regency, using a seismic microzonation approach that utilises local geotechnical and seismic data. Manna City is located in the subduction zone between the Indo-Australian and Eurasian plates, making it an area with a high risk of earthquakes. Although several studies have been conducted in the Bengkulu region, seismic microzonation research in Manna City remains limited, resulting in inadequate data support for spatial planning and the development of earthquake-resistant infrastructure. This study aims to address this gap by providing more detailed microzonation data, which is expected to produce more accurate seismic risk maps. The findings from

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this study are expected to serve as a basis for safer urban planning and implementing earthquake risk mitigation strategies in the future [1].

In 2000 and 2007, major earthquakes struck the Bengkulu region, namely the Bengkulu-Enggano earthquake and the Bengkulu-Mentawai earthquake, which damaged various vital structures in the coastal area [2]. The study showed that Bengkulu City and its surrounding areas, including Manna City, are located in the Indo-Australian and Eurasian subduction zones, making them prone to major earthquakes. 'This zone is the primary source of seismic activity in the Bengkulu region, which has caused significant structural damage in the earthquakes that occurred in 2000 and 2007 [2]. Explaining that major earthquakes in Bengkulu have caused severe damage to infrastructure and public facilities, highlighting the importance of a deeper understanding of the geological characteristics of the region for effective disaster mitigation. Therefore, conducting a more detailed assessment of earthquake risk potential in Manna, an area with high seismic amplification potential, is crucial to support earthquake-resistant spatial planning and infrastructure development [3].

Manna City is located in South Bengkulu Regency, Bengkulu Province, on the island of Sumatra, which is known as one of the areas with high potential earthquake risk due to tectonic activity in the subduction zone of the Indo-Australian plate. This study found that the area is prone to earthquakes [4]. Over the past two decades, earthquakes on the island of Sumatra specifically in the city of Bengkulu, which occurred on 4 June 2020 on Enggano Island and on 12 September 2007 in the Mentawai Islands caused significant damage [2]. The earthquake that struck Bengkulu caused severe damage to various buildings and important facilities in the area. The impact of the earthquake highlights the importance of understanding the geological and seismotectonic conditions of the area, which can influence spatial planning and disaster risk reduction [3]. Therefore, this research aims to fill the research gap in Manna City by conducting seismic microzonation based on local geotechnical and seismic data, which is important for earthquake risk mitigation and safer spatial planning [5]. Taking lessons from previous events, Bengkulu City should prioritise efforts to improve seismic hazard mitigation [6].

Earthquakes are natural phenomena caused by shifting tectonic plates that generate energy from seismic waves [1]. These vibrations can be very destructive, mainly when they occur in areas that have a particular soil structure [7]. These vibrations can be very destructive, mainly in areas with a particular soil structure [8]. Seismic microzonation, or seismic microzoning, is an approach to mapping potential earthquake hazards based on local geological and geotechnical conditions, which can modify ground shaking generated by earthquakes [9]. Seismic microzoning aims to map potential earthquake hazards by evaluating geological conditions and soil response to earthquakes. The process consists of three stages first, assessing seismic hazard based on geological data and fault activity; second, assessing soil characteristics and their dynamic response; and third, using this data to predict ground motion and potential damage that could occur to buildings and infrastructure [10]. In general, the damage caused by seismic vibrations is influenced by various factors, including the quality of the building structure, the geotechnical and topographical characteristics of the region, and the acceleration of the ground in the area experiencing the earthquake [11].

Many studies on seismic hazards have been conducted in Bengkulu. However, research focusing on the Manna City is still very limited and has not specifically examined the Manna City. Therefore, this study aims to fill the gap by conducting seismic microzonation based on local geotechnical and seismic data. Furthermore, a seismic microzonation study was conducted in several parts of Bengkulu using ground acceleration and seismic response data, which showed that areas with soft soil characteristics have a greater risk of earthquake amplification.

This research aims to analyse soil characteristics and their susceptibility to earthquakes in Manna City, using seismic microzonation based on local geotechnical and seismic data. The study results are expected to support safer infrastructure planning and disaster risk mitigation strategies in the region. Various HVSR techniques evaluate ambient noise and estimate predominant frequency, amplification, and seismic sensitivity index. This research uses geotechnical data and seismic analyses to produce microzoning maps that can be used in safer infrastructure which also spatial planning and reduce the impact of future earthquakes [12]. It can produce more accurate zoning maps and encourage the spatial plan of infrastructure that is more earthquake resistant in Manna, South Bengkulu.

In addition, this research also focuses on the application of microzoning results in spatial planning and earthquake-resistant infrastructure development in Manna City. By producing a more detailed microzoning map, local governments and urban planners can use the research results to draft disaster mitigation based development regulations. In addition, seismotectonic analyses based on the latest data in the region provide a deeper understanding of the potential earthquake hazard that has not explicitly been studied before. By integrating the research results into disaster mitigation strategies, this study is expected to significantly contribute to reducing the impact of future earthquakes and improving community and stakeholder preparedness in Manna City, South Bengkulu. Therefore, this research aims to conduct a seismic microzonation study in Manna City using an approach based on local geotechnical and seismic data.

2. Material and method

2.1. Geological conditions and seismotectonic settings

Manna City, located in South Bengkulu Regency, Bengkulu Province, has complex geological conditions due to tectonic activity and diverse soil types. The area is generally dominated by alluvial deposits (Qa) consisting of sand, silt, clay and gravel, especially in the low lands and along rivers. These deposits were formed through long-term sedimentation processes and influence local geotechnical characteristics. The presence of the Manna segment of the Sumatra Fault and secondary faults gives the region a high seismic potential. Earthquake impacts can cause significant damage to infrastructure as well as social and economic losses. Local geological conditions, including topography and soil type, play a significant role in determining the extent of damage, as was the case with the 2007 Bengkulu Mentawai Earthquake (Mw 8.6). In addition, the presence of reef limestone (Ql) along the coast indicates significant past geological activity.

Manna City is geographically located in the Indian Ocean subduction zone, where the Indo-Australian Plate collides with the Eurasian Plate. This zone is known as the Sumatra Subduction and is the primary source of seismic activity in the Bengkulu region. Several large earthquakes, such as the Bengkulu-Enggano Earthquake in 2000 and the Bengkulu Mentawai Earthquake in 2007, demonstrate the high tectonic activity in this region. In addition to subduction, the region is also influenced by the Sumatra Fault (Sumatra Fault System), which is a strike-slip fault that runs along the island of Sumatra [13]. This fault has caused several large earthquakes on the mainland, such as the Liwa Earthquake (M_w 6.8) and the Alahan Panjang Earthquake (M_w 7.9) in 1994. South Bengkulu, including Manna City, is one of the most seismic regions in Indonesia. The Bengkulu-Enggano earthquake on 4 June 2000 (M_w 7.9) is one example of the significant impact of tectonic activity, which damaged critical infrastructure in coastal areas.

This section describes how the earthquake's impact on the studied area that had researched and evaluated. Data obtained from seismic microzonation analyses, including measurements using the HVSR method, were used to assess how vulnerable the area is to earthquakes and how much potential earthquake waves are magnified in Manna City. The results show that areas with soft soils are likely to amplify earthquake vibrations, which can increase damage to buildings and infrastructure. In addition, areas with low dominant frequency (f_0 < 2.5 Hz) indicate the presence of thick sediment layers, which make the soil more responsive to earthquakes. Assessing these impacts is crucial for planning to reduce disaster risk and design more earthquake-resilient regional buildings.

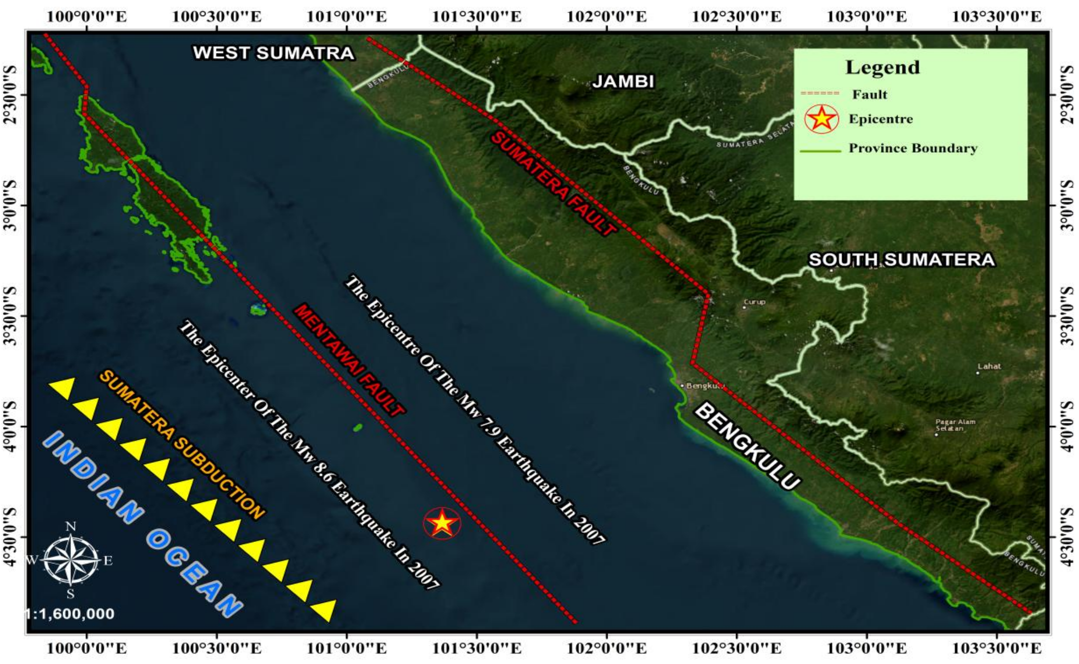

Fig. 1. Modified geological map of Bengkulu province [14].

Areas in Manna City with soft soils and high earthquake amplification are more vulnerable to damage during an earthquake, as soft soils can magnify earthquake shaking. Therefore, it is important to plan spatially by avoiding development in high-risk areas. In addition, the application of earthquake-resistant construction is essential to reduce damage. Utilisation of this microzonation data help build safer infrastructure and reduce the impact of earthquakes.

2.2. Importance of Manna City

Manna City as the capital of South Bengkulu Regency, plays a strategic role in government, economy, transport, and education and health services. This city is the centre of government administration, trade, and services and the main transportation route between districts and provinces. In addition, primary education and health facilities such as Hasanuddin Damrah Hospital are also located in the city and serve people from the surrounding areas. Fig. 1 shows the modified geological map of Bengkulu.

From a geological aspect, Manna City is located in the subduction zone between the Indo-Australian and Eurasian Plates, which causes high tectonic activity in the region. History records several significant earthquakes in the Bengkulu region, including in 1833, 2000 and 2007. One of the primary sources of earthquake potential in the region is the Manna Segment of the Sumatra Fault, with a length of approximately 85 km, a shear rate of 13.5 mm/year, and a maximum potential earthquake reaching M_w 7.3 [15].

2.3. Ambient noise microtremor

Microtremor are low-frequency ground vibrations from natural sources, such as wind and ocean waves, or human activities, such as traffic and industrial machinery. Although imperceptible to humans, these vibrations can be recorded using seismic instruments to analyse subsurface conditions. This study used measurements from various locations and applied microtremor data which use HVSR method to relate the central peak frequency to the thickness of the sedimentary layer. This relationship allows the calculation of sediment thickness at locations where the thickness is already known, proving that microtremor measurements are effective for mapping sediment layers [16]. Microtremor data provides important information on geological structures, such as the thickness of soil layers and their mechanical properties [17]. The microtremor method has been used in seismic microzonation research in Bengkulu City and Manna City. The results show the dominance of soil classes C and D based on the NEHRP classification, indicating a relatively high potential for seismic amplification [2]. This information is beneficial for the identification of earthquake-prone areas and as a basis for planning disaster resistant infrastructure.

2.4. HVSR method

The HVSR (Horizontal-to-Vertical Spectral Ratio) method estimates the fundamental resonant frequency of a site based on ambient seismic recordings [18]. The HVSR method measures the ground resonance frequency by comparing the ratio of the horizontal and vertical spectra of the microtremor signal to determine the subsurface shear wave velocity. This method is popular in seismic microzonation due to its simplicity and ease of use [19]. This analysis provides information on the dominant frequency (f_0) and amplification factor (A_0). The HVSR method is beneficial for assessing the depth of sedimentary layers and the impedance contrast between soil and bedrock. A clear peak on the HVSR curve indicates the dominant frequency, which is important for site classification and design planning of earthquake-resistant buildings [20]. In seismic microzonation, the dominant frequency describes the characteristics of the soil layer, while the amplification factor indicates the amplification of seismic waves by soft soil layers.

2.5. Amplification and Dominant frequency ranges

Analysis using the Horizontal to Vertical Spectral Ratio (HVSR) method shows ground amplification values in Manna City and Pasar Manna range from 1.3 to 5.19, with the lowest dominant frequency of 3.95 Hz and the highest of 49.71 Hz. These findings indicate variations in the amplification and frequency response of soils in the area, which can be used to identify their potential vulnerability to earthquakes [21]. Amplification increases ground vibration when seismic waves pass through soft soil layers above bedrock [22]. Amplification is an essential factor in seismic hazard assessment, as it can significantly affect the level of shaking experienced at the surface and, consequently, the potential damage to buildings and infrastructure [23]. The dominant frequency

(f_0) indicates the natural frequency of the soil when it vibrates due to an earthquake. This value is influenced by the thickness and type of soil, and can be measured using the HVSR method [18]. Low f_0 value indicates dense sediment layers, while a high value indicates more porous soil or thicker sediment [24].

2.6. Research framework

This study used a systematic approach to assess the seismic microzonation and geotechnical characteristics of Manna City. The main stages included data collection using Horizontal to Vertical Spectral Ratio (HVSR) and Multichannel Analysis of Surface Waves (MASW) method to identify soil properties and seismic response. HVSR data were used to determine the dominant frequency and amplification factor. In contrast, MASW data were used to measure the shear wave velocity to determine the depth and structure of soil layers. The results of the analyses were used to develop a seismic microzonation map showing zones with high amplification and low dominant frequency, indicating potential vulnerability to earthquakes, liquefaction and landslides. This map forms the basis for spatial planning and earthquake-resistant infrastructure development.

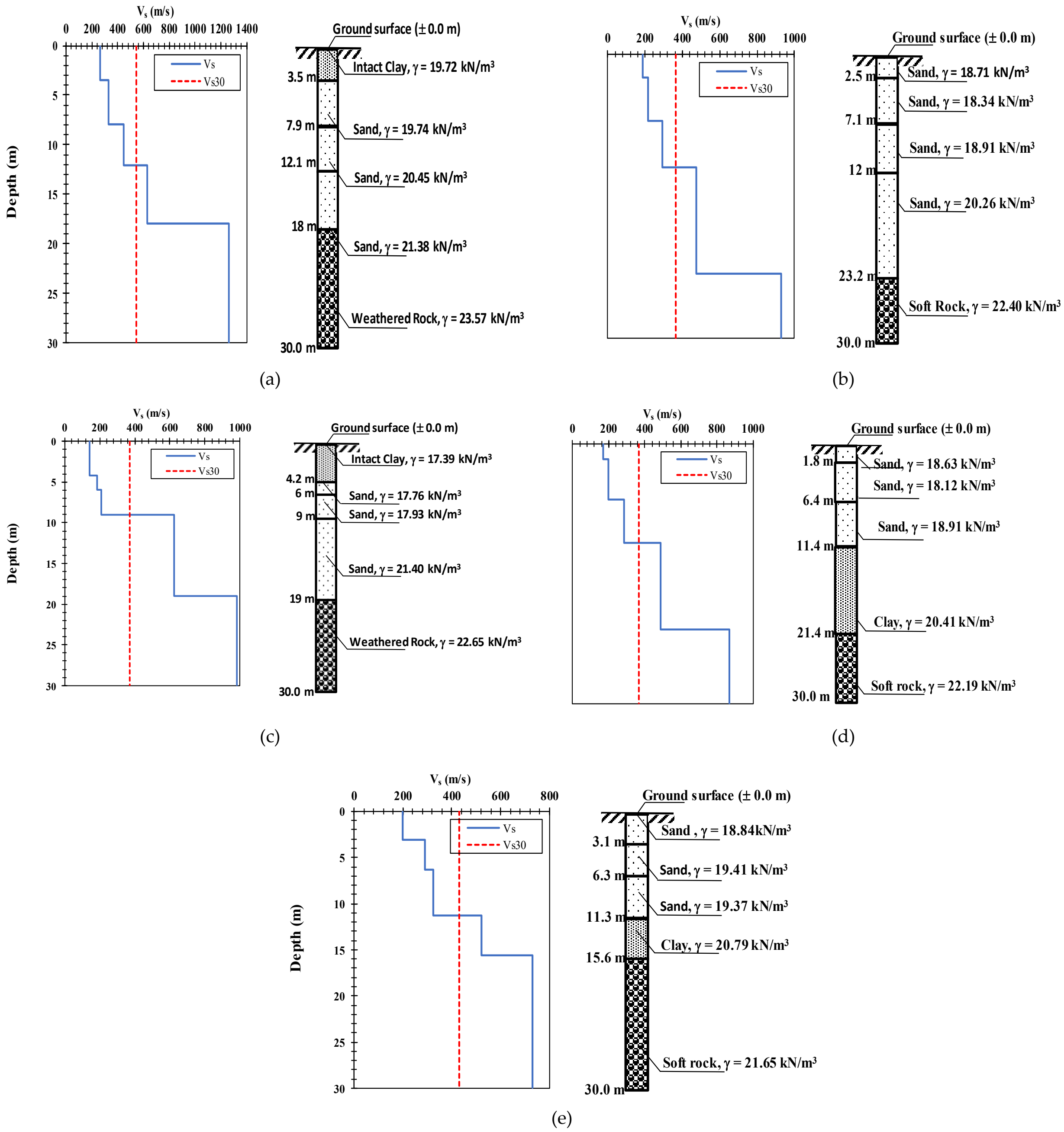

Fig. 2. Shear wave velocity profile and soil layering: (a) MN-1, (b) MN-2, (c) MN-3, (d) MN-4, (e) MN-5.

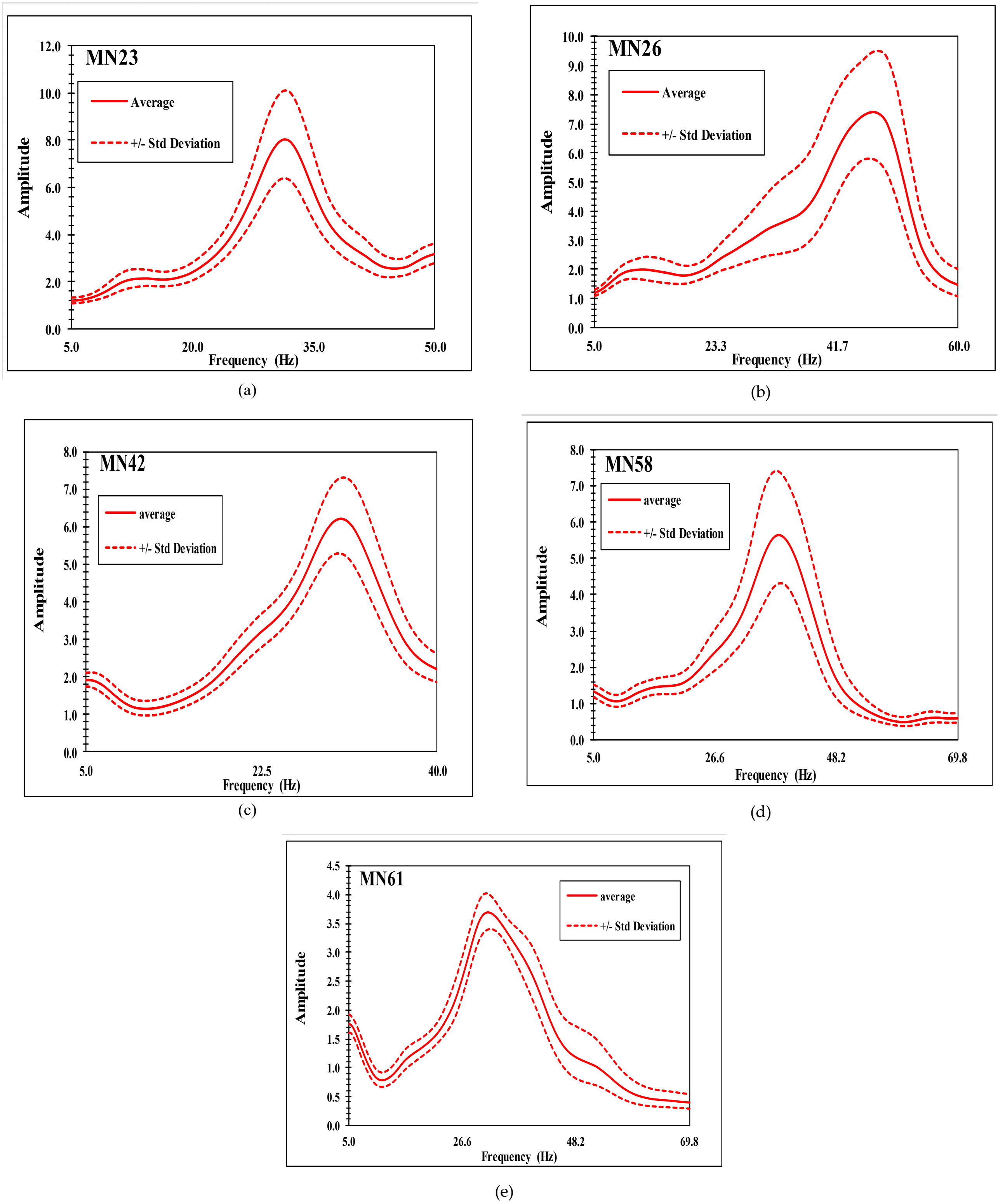

Fig. 3. HVSR Curve for sites (a) MN-1, (b) MN-2, (c) MN-3, (d) MN-4, (e) MN-5.

3. Results and discussion

3.1. Shear wave velocity profile

Shear wave velocity (V_s) profiles were obtained through dispersion curve analysis using the inversion method [6]. Fig. 2 shows that sand layers generally dominate the soil layers in this study area. The soil layers are dominated by sand because the Manna City is located in a coastal area. The National Earthquake Hazard Reduction Program (NEHRP) categorises the study area from MN-1 to MN-5 as hard soil (site class C) with an average shear wave velocity for the first 30 m (V_{s30}) of 360 to 760 m/s [25].

3.2. HVSR curve

Fig. 3 shows the HVSR (Horizontal-to-Vertical Spectral Ratio) curve, which is used to measure the dominant frequency (f_0) and amplification factor (A_0) of the soil at that location used to determine soil characteristics and the depth of subsoil rocks efficiently [26]. The HVSR analysis results show that the ground's dominant frequency in Manna City, the range is from 0.25 Hz to 14.40 Hz, with peaks in the curve indicating high seismic amplification in several areas [4]. The peak on this curve indicates a thick layer of sediment that exacerbates the impact of earthquakes in areas with high frequencies. At the same time, harder and thinner soil has higher frequencies, which are more resistant to earthquake vibrations [1]. The results of HVSR analysis are curves with peaks indicating the dominant frequency of the soil (f_0) and the amplification factor (A_0). In Manna City, variations in f_0 values reflect differences in depth and soil type. Low frequencies indicate soft and deep sediments, while high frequencies indicate harder and shallower soils. Clear peaks of the HVSR curve signify areas with high seismic amplification potential. This data is essential for creating seismic microzoning maps to identify earthquake-prone zones and support earthquake-resistant building planning and disaster mitigation-based spatial planning.

3.3. Statistical analysis

Seismic microzonation research in Manna City uses the HVSR and MASW methods to assess soil characteristics and earthquake response. The results show that areas with soft soils, especially those dominated by alluvial deposits, have high seismic amplification potential. In statistical analysis, we compare two methods for measuring soil, namely HVSR and MASW. In HVSR, two parameters are measured: the dominant frequency (f_0) and the amplification factor (A_0). In Manna City, f_0 ranges from 0.25 Hz to 14.40 Hz, where lower values indicate softer soil, and softer soil is more prone to amplifying earthquake vibrations. Meanwhile, A_0 ranges from 1.3 to 5.19, with higher values indicating that the soil can amplify earthquake vibrations more significantly. In MASW, the measured parameter is the shear wave velocity (V_s), with a range of 360 m/s to 760 m/s for Class C soil. A lower V_s indicates softer soil, which can amplify earthquake vibrations, while a higher V_s indicates more complex and stable soil. Thus, HVSR provides a quick overview of how much soil can amplify earthquake vibrations, while MASW offers more detailed information about soil type and depth. These two methods complement each other, with HVSR suitable for quick analysis and MASW providing a more comprehensive understanding of the soil. High amplification factor (A_0) were found in some locations, signalling an increased risk of building damage during an earthquake. This study updates previous research with more data and more accurate techniques, resulting in more detailed maps of amplification distribution and ground dominant frequency (f_0). Most areas have low dominant frequencies, indicating deep and soft soil layers, which tend to amplify earthquake vibrations.

These findings align with previous studies in Bengkulu Province but provide a more comprehensive understanding due to the wider coverage of measurement points. This data is important to support spatial planning and earthquake-resistant infrastructure development. The resulting microzoning map can be used as a reference in disaster mitigation policies, as it shows the vulnerable zones in more detail. Statistical data such as A_0 and f_0 are not just technical numbers, but important tools for understanding seismic risk in an area.

3.4. Amplification map

The amplification factor (A_0) describes how much seismic waves are amplified due to differences in the nature of geological layers [27]. Based on the distribution map of A_0 in Manna City (see Fig. 4), amplification values range from 1.3 to 5.19. High A_0 values are generally found in areas with soft soil, which is more susceptible to amplifying earthquake vibrations [27, 28]. Buildings with a height of 1 to 2 storeys in Pino Raya and Manna City sub districts, as well as those with a height of 1 to 4 storeys in Pasar Manna sub-district, are at risk of being exposed to stronger vibrations when an earthquake occurs. Therefore, it is important to consider the level of seismic amplification when designing buildings and to select materials and construction techniques that can reduce the impact of such seismic vibrations. Areas with soft soils, especially those with river sediment layers, tend to have a higher risk of seismic amplification. This means that earthquake vibrations will be stronger in these areas, which can increase the likelihood of damage to buildings. When the amplification factor (A_0) is high, especially in places with soft soils, the earthquake's impact may be greater and may damage building structures. With regulations requiring construction to consider earthquake mitigation, safer infrastructure can be realised. Using seismic microzoning data in development planning will help reduce the damage that earthquakes can cause.

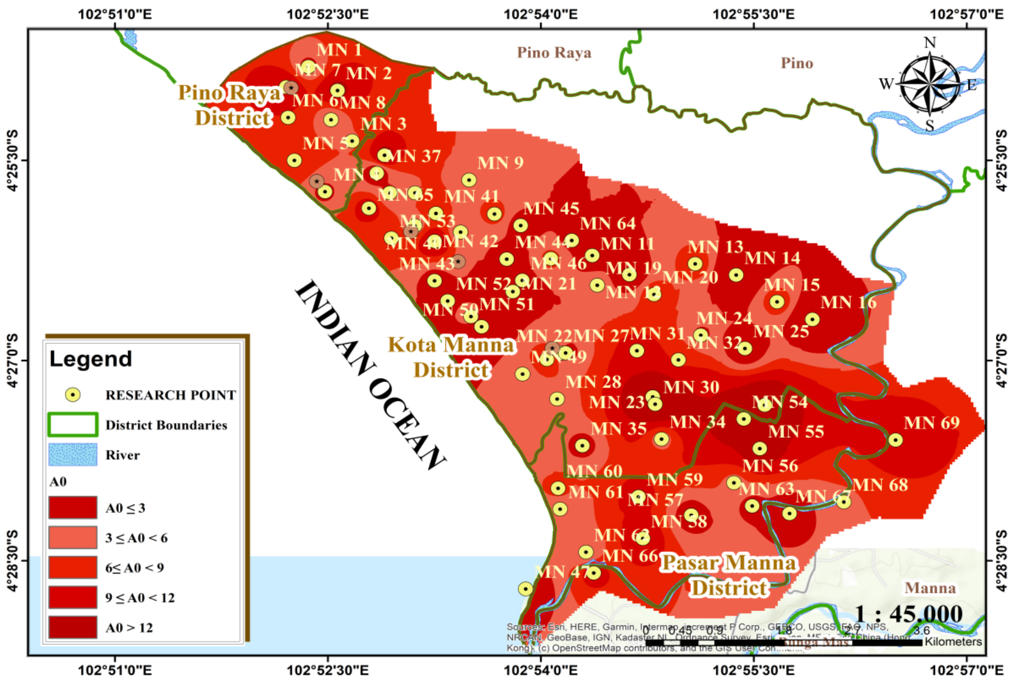

Fig. 4. A_0 distribution map.

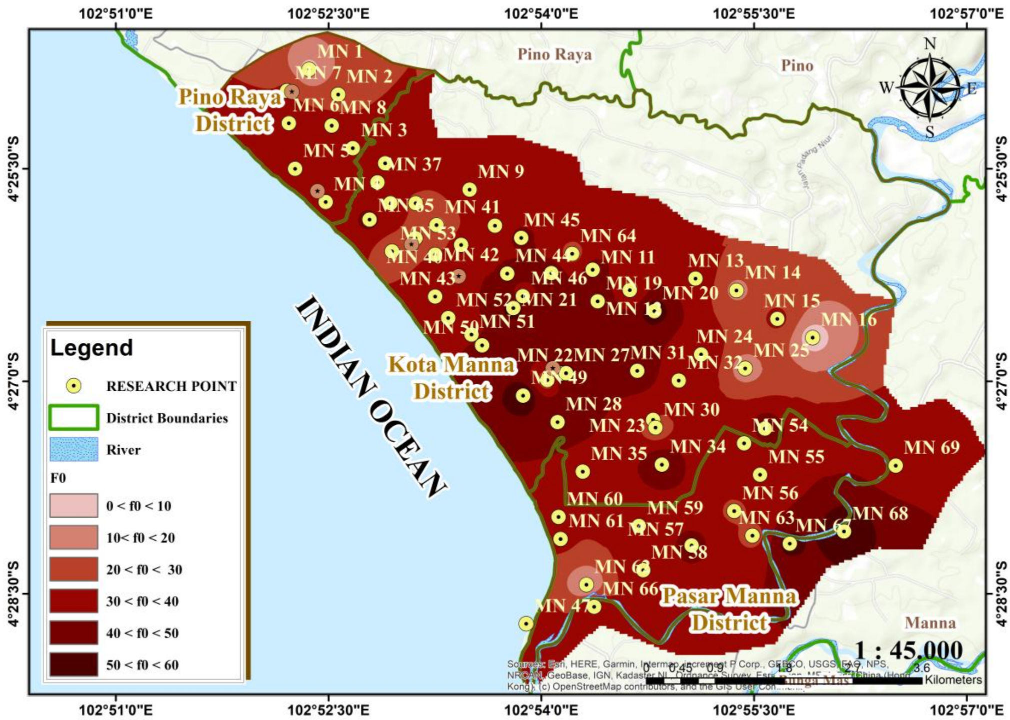

Fig. 5. Distribution map of natural frequency (f_0).

3.5. Dominant frequency map

The dominant frequency (f_0) indicates the soil's natural vibration, which is influenced by soil thickness and hardness. Fig. 5 shows that soft and thick soil has a low f_0, while hard and thin soil has a high f_0. In Manna City, Pasar Manna , and Pino Raya, the f_0 values range from 0.25 Hz to 14.40 Hz. This indicates that the soil in these areas is harder and thinner, making it more stable in withstanding earthquake vibrations.

This data is crucial for identifying earthquake-prone zones and informing the planning of earthquake-resistant buildings. The Pino Raya and Manna City sub-districts have a higher base frequency, meaning that these areas are more resistant to earthquakes than the sub-district of Pasar Manna. Zones with high dominant frequency are found in some areas, such as Pasar Manna and Pino Raya, indicating that these regions have thick sediment layers and soft soil, which amplify the soil's response to earthquakes.

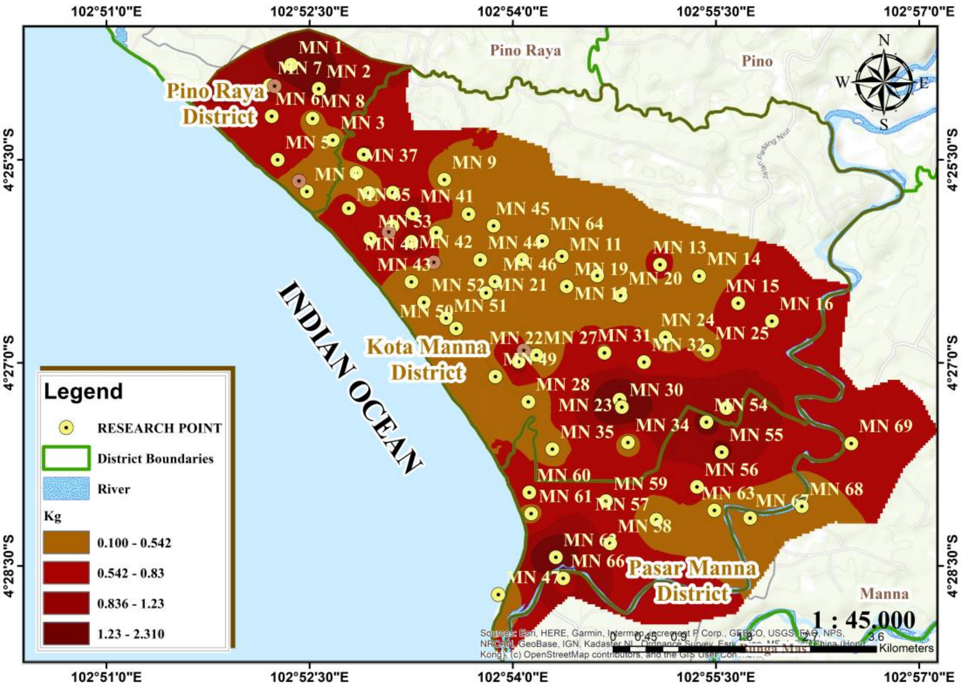

Fig. 6. Distribution map of seismic vulnerability index values (K_g).

3.6. Seismic Vulnerability Index

Fig. 6 in this study analyses microtremor data from 69 points in South Bengkulu Regency using the HVSR method. The results indicate that this region, including Manna City, has relatively high earthquake shaking potential. This is evident from the amplification factor (A_0) ranges from 1.3 to 5.19 and dominant frequency (f_0) between 0.25 Hz and 14.40 Hz, generally indicating hard and thin soils with a high risk of vibration amplification. The earthquake vulnerability index (K_g) values are also relatively low, ranges from 0.26 to 11.78, indicating that most of the area is not vulnerable to structural damage from light to moderate earthquakes. However, this does not mean the area is completely safe. Tectonically, Bengkulu Province is in an active subduction zone that can potentially trigger major earthquakes. Therefore, despite the high local risk, mitigation efforts such as earthquake-resistant construction and increased preparedness remain crucial. The K_g value can be used as a predictive tool to identify weak zones and plan risk reduction strategies before an earthquake occurs [18], [30].

3.7. Building stories suitability recommendation

As a result of seismic microzonation research in Manna city, the region has a high potential for seismic amplification, especially in areas with soft soils, so buildings constructed there should use sturdy structures and materials capable of reducing the impact of earthquake shaking. In addition, it is important to pay attention to the dominant frequency of the soil (f_0) as soils with low frequencies can exacerbate the impact of earthquake shaking. For buildings with a height of 1-3 storeys, it is recommended that the resonance period of the building be adjusted to the dominant period of the soil (T_0), in order to avoid resonance that could worsen damage during an earthquake.

On the other hand, the seismic vulnerability index (K_g) shows that some areas in Manna City are at higher risk of earthquake damage. Therefore, buildings in these areas must have earthquake vibration-damping systems and stronger structural designs. For multi storey buildings of more than two storeys, it is recommended to utilise seismic isolation technology that can help reduce the impact of larger earthquake vibrations.

Applying the SNI 1726:2019 standard is essential for more effective building planning, as this standard requires using local geotechnical data and seismic microzonation results in building design. Following these recommendations is expected to reduce potential earthquake damage, increase building resilience, and strengthen disaster mitigation efforts in Manna City.

4. Conclusions

Seismic microzonation research in Manna City shows that the level of earthquake vulnerability is influenced by soil type and geological conditions. Areas with soft soils and thick sediments have a high potential for earthquake amplification. At the same time, low dominant frequency (f_0) values indicate the presence of deep, less dense soil layers, which can amplify earthquake vibrations. Most areas have a low seismic vulnerability index (K_g), but some spots show higher vulnerability.

The MASW method measures shear wave velocity (V_s), where low V_s values indicate soils more susceptible to seismic wave amplification. The resulting microzoning maps can be used to design earthquake-resistant buildings and determine vulnerable zones. This research also emphasises the importance of matching the dominant period of the soil (T-site) with the natural period of the building (T-building) to avoid the risk of harmful resonance, especially in 1-3 storey buildings. Therefore, the use of microzoning maps and the application of SNI 1726:2019 are essential in infrastructure planning and earthquake risk mitigation in this region.

Areas in Manna City that have high earthquake amplification and soft soil conditions are more vulnerable to severe damage during an earthquake. Therefore, the use of seismic microzoning maps is important in urban spatial planning to ensure that development is avoided in areas with a high risk of earthquake impacts. In addition, implementing regulations that require development to consider earthquake mitigation will ensure the safety of buildings and settlements. By utilising seismic microzoning data, future development planning is expected to reduce earthquake damage.

Declaration statement

Aza Geby Anjelah: Collecting data, Writing-Original Draft. **Lindung Zalbuin Mase, Khairul Amri**: Methodology, Conceptualization. **Rena Misliniyati, Hardiansyah**: Methodology, Writing-Review & Editing.

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Disclosure statement

This research states that areas of Manna City with soft soil characteristics and high amplification values have the potential for greater damage due to earthquakes, so integrating microzonation data is needed in spatial planning and earthquake-resistant infrastructure development.

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This research did not receive funding support from any government, private, commercial or non-profit organisation.

Data availability statement

The data used in this study are not publicly available due to privacy considerations of measurement sites and institutional policies. However, the correspondence author can provide data upon reasonable request for academic and non-commercial purposes.

AI Usage Statement

This research did not use artificial intelligence (AI) in data analysis or interpretation of results. However, generative AI tools were used on a limited basis for language editing and scientific writing style adjustments during the drafting process.

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