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CHARACTERIZATION OF TELUK SEPANG COASTAL LOCAL SEISMIC RESPONSE USING MICROTREMOR HVSR ANALYSIS

KARAKTERISASI RESPON SEISMIK LOKAL PESISIR TELUK SEPANG MENGGUNAKAN ANALISIS MICROTREMOR HVSR

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Abstract. The coastal area of Teluk Sepang, Bengkulu City, Sumatra, Indonesia, is dominated by young alluvial and marine sediments that are highly susceptible to seismic wave amplification due to tectonic activity along the Indo-Australian–Eurasian subduction zone. This research aims to characterize local seismic response and map soil dynamic properties using microtremor data analyzed with the Horizontal to Vertical Spectral Ratio (HVSR) method. Microtremor measurements were conducted at several observation points with a sampling interval of 5 ms capable of and a recording duration of 30 minutes at each site. The recorded data were processed using the HVSR method through windowing, Fourier transform, and spectral ratio analysis to obtain the dominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (Kg). The results show that low f_0 values are associated with thick soft sediments, while high A_0 values indicate stronger amplification potential. High Kg values are identified in areas where low f_0 coincides with high A_0, reflecting greater seismic vulnerability. These results reveal significant spatial variability in local seismic response across the study area. This study provides new site-specific insights into seismic vulnerability in coastal environments and contributes to improving seismic hazard assessment and coastal development planning in Bengkulu City.

Abstrak. *Wilayah pesisir Teluk Sepang, Kota Bengkulu, Sumatra, Indonesia, didominasi oleh sedimen aluvial dan laut muda yang sangat rentan terhadap amplifikasi gelombang seismik akibat aktivitas tektonik di sepanjang zona subduksi Indo-Australia–Eurasia. Penelitian ini bertujuan untuk mengkarakterisasi respons seismik lokal dan memetakan sifat dinamis tanah menggunakan data mikrotremor yang dianalisis dengan metode Rasio Spektral Horizontal ke Vertikal (HVSR). Pengukuran* *mikrotremor dilakukan di beberapa titik pengamatan dengan interval pengambilan sampel 5 ms dan durasi perekaman 30 menit di setiap lokasi. Data yang direkam diproses menggunakan metode HVSR melalui windowing, transformasi Fourier, dan analisis rasio spektral untuk mendapatkan frekuensi dominan (f_0), faktor amplifikasi (A_0), dan indeks kerentanan seismik (Kg). Hasil menunjukkan bahwa nilai f_0 yang rendah dikaitkan dengan sedimen lunak yang tebal, sedangkan nilai A_0 yang tinggi menunjukkan potensi amplifikasi yang lebih kuat. Nilai Kg yang tinggi diidentifikasi di daerah-daerah di mana f_0 rendah bertepatan dengan A_0 tinggi, yang mencerminkan kerentanan seismik yang lebih besar. Hasil ini mengungkapkan variabilitas spasial yang signifikan dalam respons seismik lokal di seluruh wilayah studi. Studi ini memberikan wawasan baru yang spesifik lokasi tentang kerentanan seismik di lingkungan pesisir dan berkontribusi pada peningkatan penilaian bahaya seismik dan perencanaan pembangunan pesisir di Kota Bengkulu.*

1. INTRODUCTION

The coastal area of Bengkulu City is located in a highly active tectonic setting influenced by the Indo-Australian–Eurasian subduction zone, which has generated numerous destructive earthquakes in western Sumatra. This tectonic environment, combined with the presence of young coastal and alluvial deposits, makes the region particularly vulnerable to local seismic amplification and ground motion intensification (Harlianto et al., 2024; Falah et al., 2023).

Local seismic response is strongly controlled by shallow subsurface conditions, especially sediment thickness, stiffness, and the impedance contrast between surface layers and bedrock. Thick and unconsolidated sediments tend to exhibit low dominant frequencies and high amplification potential, thereby increasing seismic risk in coastal and lowland areas (Parolai et al., 2002; Mase et al., 2021; Kencoro et al., 2023). The Horizontal to Vertical Spectral Ratio (HVSR) method, first introduced by Nakamura (1989), has been widely applied as a non-destructive and cost-effective approach for estimating site resonance characteristics based on ambient vibration records (Nakamura, 1989; Wathelet et al., 2020; Issaadi et al., 2020; Susilo et al., 2024). HVSR analysis is particularly effective in areas with thick sedimentary layers and complex subsurface structures, allowing the estimation of the dominant frequency (f_0) and amplification factor (A_0), which represent key indicators of local seismic response (Bonnefoy-Claudet et al., 2006; Castellaro & Mulargia, 2009; Wathelet et al., 2020; Tawakal et al., 2020).

The seismic vulnerability index (Kg) has been widely used as an indicator of site susceptibility in areas dominated by soft sediments, particularly for seismic microzonation and hazard assessment (Mase et al., 2021; Fatimah et al., 2022; Ariyanto et al., 2024; Farduwin et al., 2025). Previous studies in Indonesia have successfully applied HVSR-based parameters and Kg for seismic microzonation and site characterization (Hesti et al., 2021), however, most of these studies focus on inland or urban areas rather than coastal environments (Mase et al., 2021; Fatimah et al., 2022; Susilo et al., 2024). Despite the high seismic risk in the Bengkulu coastal area, HVSR-based characterization in coastal settings such as Teluk Sepang remains limited. Previous studies have generally focused on inland or urban environments, with less attention given to coastal zones dominated by young alluvial and marine sediments (Simanjuntak et al., 2021; Stephenson, 2007). As a result, the spatial variability of local seismic response in coastal sedimentary environments is still not well understood, particularly in relation to the combined behaviour of dominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (Kg).

To address this gap, this study provides this gap by providing a detailed site-specific analysis of local seismic response in Teluk Sepang coastal area using integrated HVSR-based mapping of f_0, A_0, and Kg. The novelty of this research lies in its focus on a coastal sedimentary environment that has not been previously investigated in detail, as well as in the combined interpretation of multiple HVSR-derived parameters to better characterize seismic vulnerability. Therefore, this research contributes to improving the understanding of local seismic response in coastal areas and provides a more comprehensive basis for seismic hazard assessment and coastal development planning in Bengkulu City.

2. LITERATURE REVIEW

The local seismic response of an area is greatly influenced by shallow geological conditions, specifically the thickness and physical properties of surface sediments. Thick soft sediment layers tend to have low dominant frequencies and are able to amplify seismic waves due to the impedance contrast with bedrock, thereby increasing the amplification potential of ground motion at the surface (Parolai et al., 2002).

The microtremor method is a widely used non-destructive approach for identifying the dynamic characteristics of shallow soils. Nakamura (1989) introduced the Horizontal to Vertical Spectral Ratio (HVSR) method to determine the resonant frequency of the ground based on the ratio of horizontal to vertical vibration spectra. This method is effectively applied in areas with thick sediments and complex subsurface structures because it can efficiently represent local seismic responses.

The main parameters obtained from HVSR analysis include the dominant frequency of the soil (f_0) and the amplification factor (A_0). The variation of f_0 and A_0 reflects the lateral heterogeneity of soil dynamic conditions (Issaadi et al., 2020).

To integrate dominant frequency and amplification information, the seismic vulnerability index (Kg) is calculated from a combination of f_0 and A_0 parameters. This index is used as an early indicator of the potential for local seismic amplification and the characteristics of soil seismic response. The parameters f_0, A_0, and Kg together provide a strong theoretical basis for mapping local seismic responses and evaluating soil dynamic conditions in areas dominated by soft sediments (Fatimah et al., 2022).

3. RESEARCH METHODS

3.1. Research Location

This research was conducted in Teluk Sepang Village, Bengkulu City, Sumatra, Indonesia which geomorphologically is a coastal area dominated by young sediment deposits. The selection of the site is based on its shallow geological characteristics, consisting of coastal and alluvial deposits, as well as its proximity to active tectonic zones, thus potentially exhibiting significant variations in local seismic responses.

A total of 8 microtremor measurement points were distributed in a representative manner to capture variations in subsurface conditions across the study area (**Figure 1**). The selection of measurement points also considered relatively flat ground surface conditions, distance from artificial disturbance sources, and low ambient noise levels, so that the recorded ambient vibration data reflect the natural dynamic conditions of the soil.

3.2. Microtremor Data Acquisition

Data acquisition was carried out using a set of Geophone/Surface Gemini-2 3D microtremor devices. At each measurement point, recordings were performed with a sampling interval of 5 ms and a duration of 30 minutes to ensure signal stability and to capture ambient vibration characteristics within the low to medium frequency range relevant to local seismic response.

The relatively long recording duration ensures sufficient data for optimal window selection and spectral analysis, while minimizing the influence of non-stationary transient noise, in accordance with the SESAME guidelines (SESAME, 2004).

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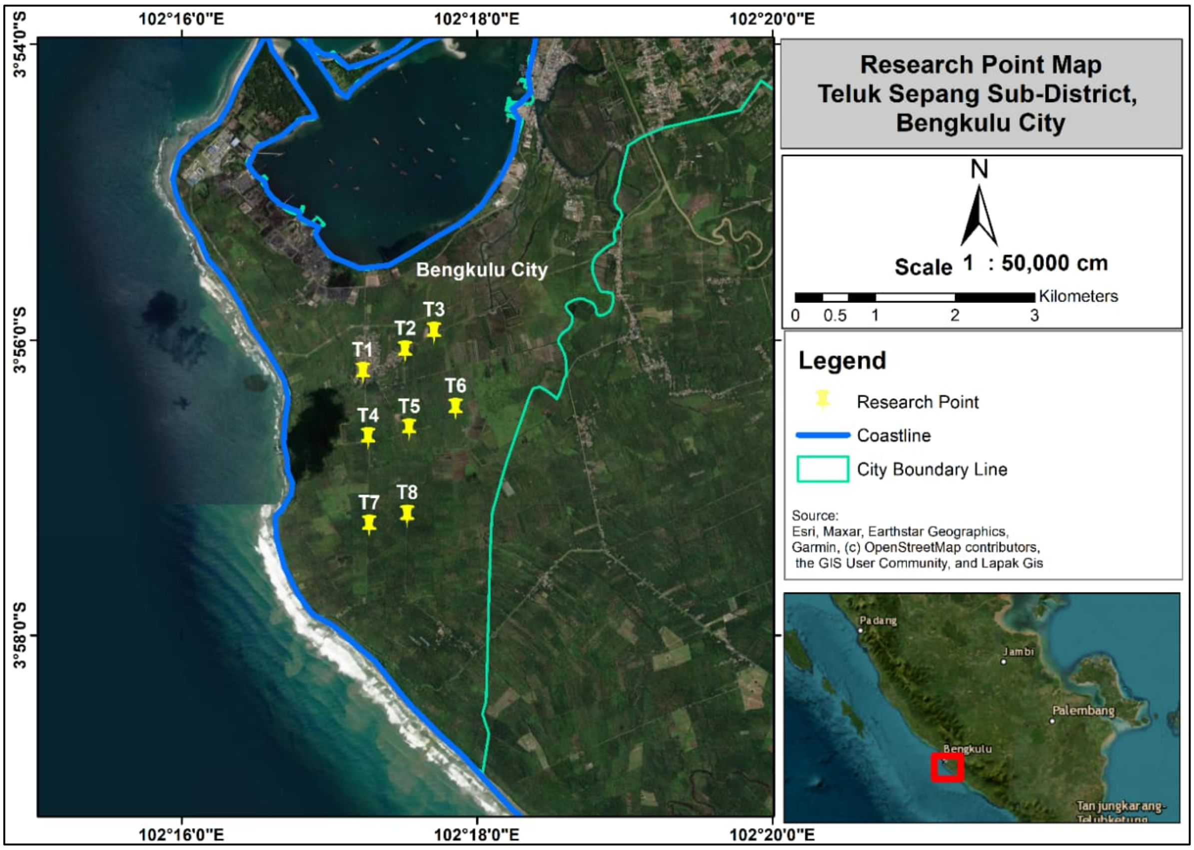

Figure 1. Location map of the study area in Teluk Sepang, Bengkulu City, Sumatra showing the distribution of microtremor measurement points used for HVSR analysis.

3.3. HVSR Data Processing and Analysis

The recorded microtremor data were processed using the Horizontal to Vertical Spectral Ratio (HVSR) method. The processing stage began with the selection of data segments (windowing) that were free from transient disturbances, such as human activities or other sources of artificial vibrations. Each selected window was then transformed into the frequency domain using a Fourier transform to obtain the amplitude spectrum of each component

The HVSR ratio was calculated by comparing the average spectrum of the horizontal components to that of the vertical component. From the resulting HVSR curve, the dominantvulnerability index frequency (f_0), identified as the main peak of the curve, and the amplification factor (A_0), defined as the amplitude at the dominant frequency, were determined. The f_0 parameter represents site resonance, while A_0 reflects amplification potential.

The quality and reliability of the HVSR curves were evaluated based on the SESAME guidelines, including the presence of a clear and stable peak, low noise levels, and consistency of the dominant frequency across multiple time windows. Only data that fulfilled these criteria were considered reliable and used for further analysis.

The frequency range analyzed in this study was approximately 0.5–10 Hz, which is suitable for identifying site resonance characteristics in shallow sedimentary environments.

This methodology provides a consistent and reliable framework for characterizing local seismic response.

3.4. Determination of Seismic Vulnerability Index

To integrate the dominant frequency and amplification information, the seismic vulnerability index (Kg) is calculated based on the combination of f_0 and A_0 parameters. The Kg value is defined as:

$$Kg = \frac{A0^2}{f0} \quad (1)$$

where A_0 is the amplification factor and f_0 is the dominant frequency (Siagian et al., 2025). This index is used as an indicator of the potential level of local seismic response and amplification potential in shallow sediments. The f_0, A_0, and Kg values of all measurement points were then mapped spatially using interpolation methods to illustrate variations in soil dynamic characteristics in the Teluk Sepang area. The maps were used to identify patterns of shallow sediment distribution and zones with relatively higher shock amplification potential.

3.5. Interpolation and Uncertainty Analysis

Spatial interpolation of the HVSR-derived parameters (f_0, A_0, and Kg) was performed to generate continuous distribution maps across the study area. The interpolation was conducted using the Inverse Distance Weighting (IDW) method, which assumes that points closer to the observation location have a greater influence on the estimated values than those farther away. This method was selected due to the relatively limited number of measurement points and its effectiveness in representing spatial variability in geophysical data.

The quality of the HVSR curves was evaluated based on the SESAME (2004) guidelines, including the clarity and stability of the peak frequency, low noise levels, and consistency across selected time windows. Only HVSR curves that exhibited a clear and stable peak were considered reliable for determining the dominant frequency (f_0) and amplification factor (A_0).

In addition, uncertainty in the results may arise from several factors, including the limited spatial distribution of measurement points, local noise conditions, and the assumption of a one-dimensional subsurface structure inherent in the HVSR method. Although these limitations may affect the resolution of the resulting maps, the overall spatial patterns obtained are considered representative of the general subsurface conditions in the Teluk Sepang area.

4. RESULTS AND DISCUSSION

Overall, the spatial variations observed in dominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (Kg) are not only indicative of heterogeneous subsurface conditions but also reflect the underlying geophysical controls governing local seismic response.

The occurrence of low f_0 values in several parts of the study area can be physically explained by the presence of thick, unconsolidated sediment layers, which reduce the natural resonance frequency of the ground. According to the fundamental resonance theory, f_0 is inversely proportional to sediment thickness and directly related to shear-wave velocity. Therefore, thicker and softer sediments tend to produce lower resonance frequencies.

In contrast, high A_0 values are associated with strong impedance contrasts between soft surface sediments and the underlying stiffer layers. This contrast enhances the trapping and amplification of seismic wave energy within the sedimentary column. As a result, areas exhibiting both low f_0 and high A_0 represent zones where thick soft sediments overlie more competent materials, leading to significant amplification effects.

This combined behaviour directly influences the distribution of high Kg values, which highlights zones of increased seismic vulnerability. Similar relationships between low f_0, high amplification, and elevated seismic risk have been reported in previous HVSR-based studies (Parolai et al., 2002; Mase et al., 2021; Fatimah et al., 2022), confirming that sediment thickness and impedance contrast are primary controls on local seismic response.

4.1. Dominant Frequency Map (f_0)

As shown in **Figure 2**, the dominant frequency (f_0) distribution in Teluk Sepang Village exhibits relatively low to moderate variation. Low f_0 values (< 1–1.5 Hz) are predominantly distributed in the northern and central parts of the study area, while higher f_0 values (> 2.5 Hz) tend to occur in the southern part.

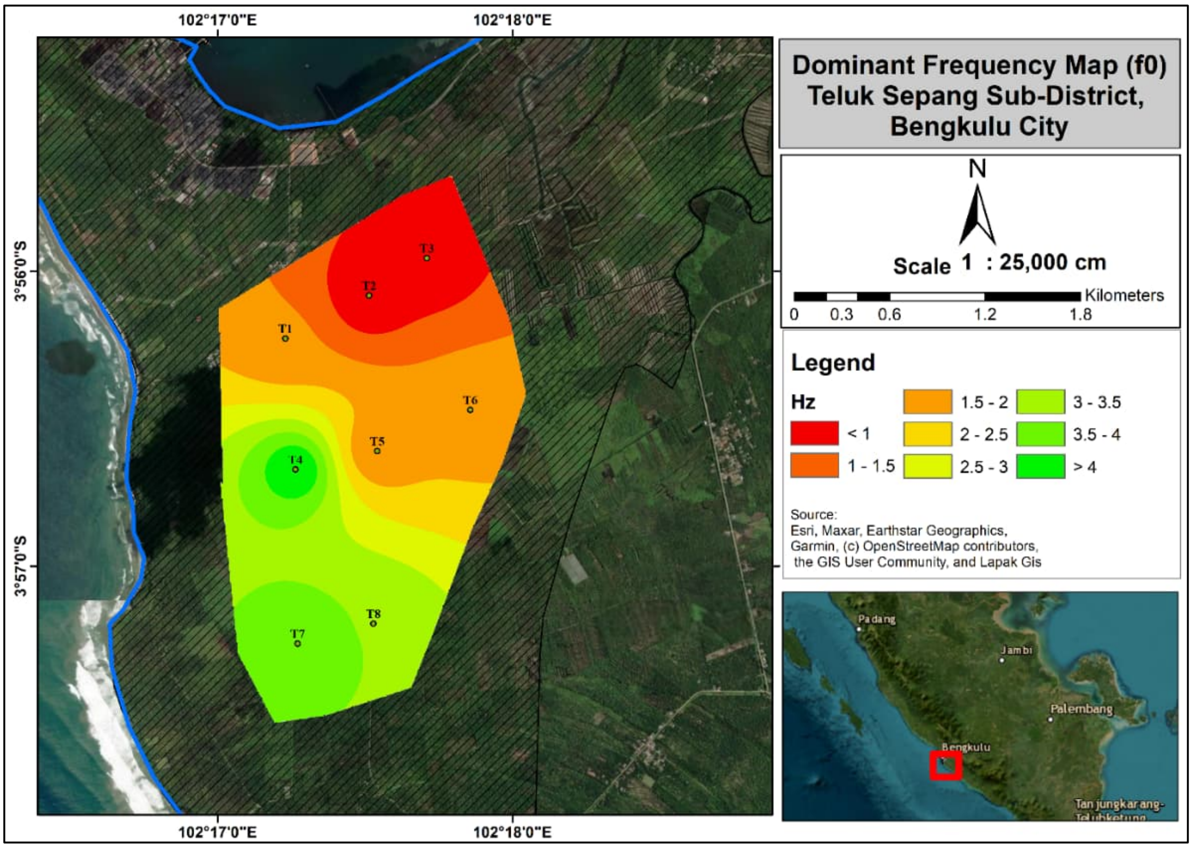

Figure 2. Spatial distribution map of dominant frequency (f_0) in the Teluk Sepang area derived from HVSR analysis, indicating variations in sediment thickness and subsurface conditions.

This variation reflects differences in subsurface geological conditions, particularly sediment thickness and stiffness. Low f_0 values are associated with thick, unconsolidated sediments with low shear-wave velocity, which reduce the natural resonance frequency of the ground. In contrast, higher f_0 values indicate thinner sediment layers or the presence of more compact and stiffer materials, suggesting a shallower depth to bedrock.

The dominance of low f_0 values in the northern and central areas suggests the accumulation of young coastal and alluvial deposits, which are typically characterized by high porosity and low mechanical strength. Such conditions are consistent with coastal depositional environments, where continuous sedimentation leads to significant lateral variability in sediment thickness. Similar findings have been reported in previous studies, where low dominant frequencies are strongly correlated with thick soft sediment layers (Mase et al., 2021; Kencoro et al., 2023).

4.2. Amplification Map (A_0)

As shown in **Figure 3**, the amplification factor (A_0) exhibits significant spatial variation, particularly in the northern and southern parts of the study area. Low to moderate A_0 values (< 1.5) dominate the central part of the region, while high A_0 values > 2.0) are concentrated in the northern and southern parts of the Teluk Sepang area.

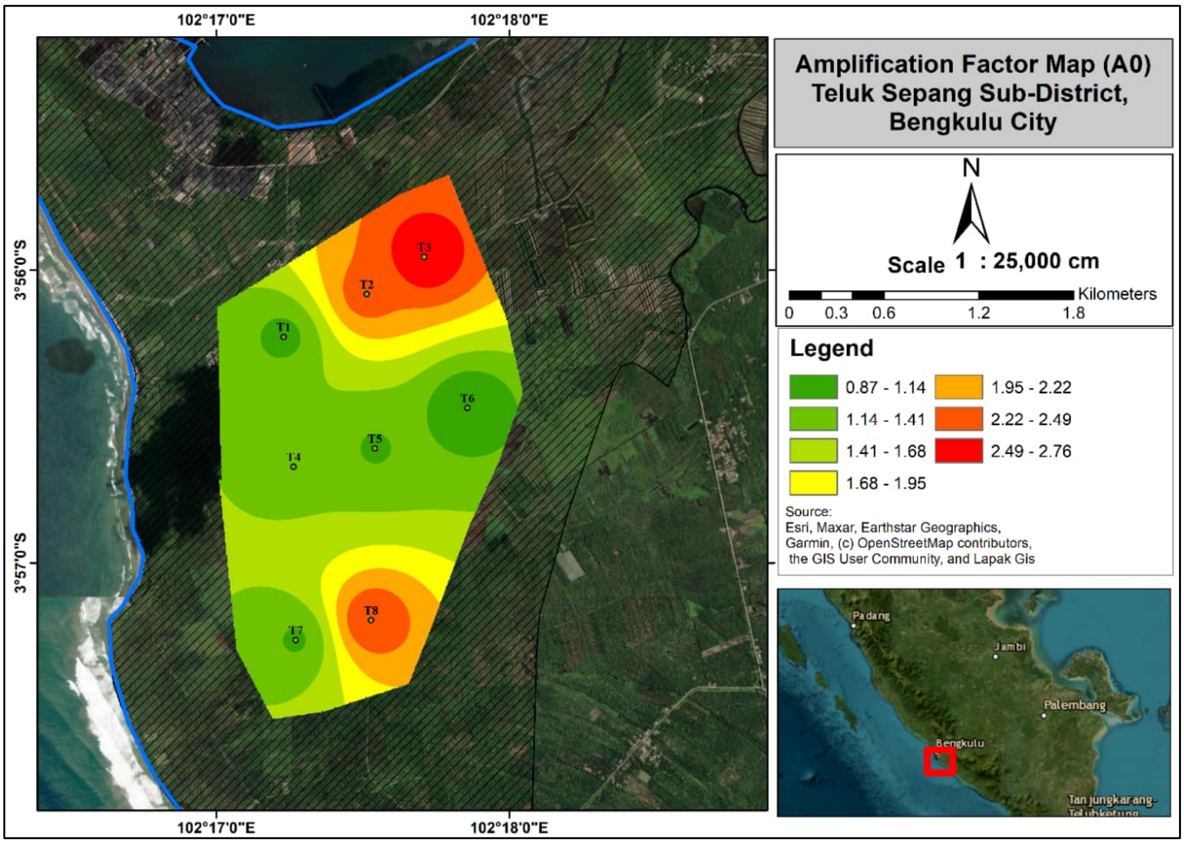

Figure 3. Spatial distribution map of amplification factor (A_0) in the Teluk Sepang area obtained from HVSR analysis, showing zones with varying levels of seismic wave amplification.

This spatial variation is primarily controlled by the impedance contrast between subsurface layers. High A_0 values indicate strong contrasts between low-velocity surface sediments and underlying stiffer materials, which enhance the trapping and amplification of seismic wave energy within the sedimentary layers. In such conditions, seismic waves undergo multiple reflections and constructive interference, leading to increased ground motion amplitude at the surface.

In addition, the presence of fine-grained, unconsolidated, and potentially water-saturated sediments in coastal environments further reduces shear-wave velocity, thereby increasing amplification effects. Conversely, lower A_0 values in the central part of the study area suggest relatively more compact or homogeneous subsurface conditions, where impedance contrasts are less pronounced and seismic wave amplification is reduced.

These results are consistent with previous studies (Parolai et al., 2002; Fatimah et al., 2022), which demonstrate that high amplification is strongly associated with soft sediment layers and significant impedance contrasts in shallow subsurface structures.

4.3. Earthquake Vulnerability Distribution Map (Kg)

The seismic vulnerability index (Kg) map shows a clear pattern of vulnerability zoning in the Teluk Sepang area (**Figure 4**). Low Kg values (< 2–4) are generally distributed in the central to southern parts of the study area, while high Kg values (> 8 to > 10) are concentrated in the northern part of the region.

The observed distribution of Kg is physically controlled by the combined effects of dominant frequency (f_0) and amplification factor (A_0). High Kg values occur in areas where low f_0 coincides with high A_0, indicating thick, unconsolidated sediment layers overlying stiffer materials with strong impedance contrast. This condition enhances both resonance and amplification processes, leading to increased seismic wave energy at the ground surface.

In contrast, low Kg values reflect relatively more stable subsurface conditions, characterized by higher dominant frequencies and lower amplification factors, which indicate thinner sediments or more compact and homogeneous materials.

From a hazard perspective, zones with high Kg values are associated with a greater risk of structural damage due to strong ground motion amplification in soft sediment environments. In addition, such geological conditions may increase susceptibility to secondary hazards, including ground settlement and liquefaction, particularly in water-saturated and unconsolidated coastal deposits (Mase et al., 2021; Parolai et al., 2002).

These findings are consistent with previous studies (Fatimah et al., 2022; Susilo et al., 2024), which highlight that areas characterized by low f_0 and high amplification tend to exhibit elevated seismic vulnerability. Therefore, the spatial distribution of Kg provides an integrated and reliable indicator of local seismic response and should be considered in seismic design and mitigation planning.

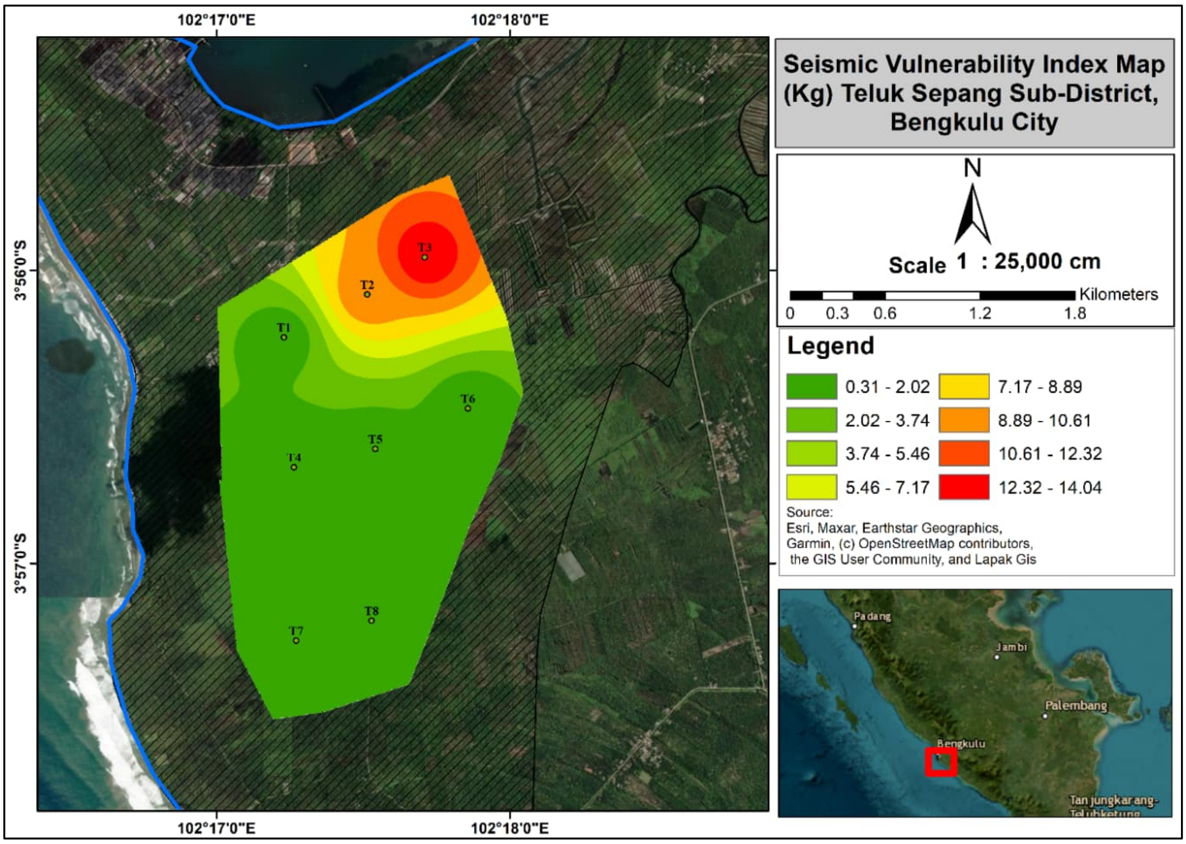

Figure 4. Spatial distribution map of seismic vulnerability index (Kg) in the Teluk Sepang area, illustrating zones with different levels of seismic vulnerability based on the combination of f_0 and A_0 parameters.

5. CONCLUSION

This study demonstrates that the HVSR method is effective in identifying soil dynamic characteristics and shallow sediment heterogeneity in the Teluk Sepang coastal area. Variations in dominant frequency (f_0), amplification factor (A_0), and seismic vulnerability index (Kg) indicate that several zones are composed of thick soft sediments with a strong potential for seismic wave amplification. The spatial distribution of these parameters reflects the influence of local geomorphological and stratigraphic conditions.

The dominance of low f_0 values in the northern and central parts of the study area indicates the presence of thick unconsolidated coastal and alluvial sediments, which are associated with low shear-wave velocities and high amplification potential. In contrast, higher f_0 values observed in the southern part suggest relatively thinner sediment layers or the presence of stiffer subsurface materials, highlighting the spatial variability of sediment thickness and depositional processes.

The findings confirm that areas characterized by low f_0 and high A_0 values correspond to zones with higher seismic vulnerability. The integration of f_0, A_0, and Kg provides quantitative evidence that the Teluk Sepang area exhibits clear spatial variation in seismic hazard potential.

From a seismic hazard mitigation perspective, zones with low f_0, high A_0, and high Kg values should be considered priority areas for risk management. These areas require careful consideration in land-use planning, particularly for critical infrastructure such as residential areas, transportation networks, and public facilities. The integration of HVSR-based parameters with regional geological understanding provides a comprehensive basis for seismic microzonation and supports the development of site-specific earthquake mitigation strategies in coastal regions of Bengkulu City.

Further research is recommended to integrate HVSR results with surface wave-based geophysical surveys or geotechnical testing to obtain more reliable V_{s30} models and subsurface structures. This approach will improve the interpretation of seismic vulnerability and provide a stronger scientific basis for earthquake risk assessment in coastal environments.

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