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Seismic Microzonation in Padaherang Subdistrict Using Microtremor Analysis for Disaster Risk Mitigation

Tio Azhar Prakoso Setiadi[1,*], Agustya Adi Martha[1], Bayu Sutejo[1],
Supriyanto Rohadi[2], Rahmat Setyo Yuliatmoko[2]

[1]National Research and Innovation Agency (BRIN), Soekarno Science and Technology Park
(Kawasan Sains dan Teknologi Soekarno), Jalan Raya Jakarta–Bogor Km. 46, Cibinong, Bogor,
West Java 16911, Indonesia
[2]Agency for Meteorology, Climatology, and Geophysics (BMKG), Jalan Angkasa I No. 2,
Kemayoran, Jakarta 10720, Indonesia

*Author to whom correspondence should be addressed:
E-mail: tioa001@brin.go.id

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Abstract: This research aims to evaluate earthquake vulnerability in the Padaherang Subdistrict by utilizing microtremor measurements, focusing on the area's geological characteristics. This study involved 64 measurement points distributed across Padaherang Subdistrict. The presence of soft and thick sediment layers, particularly alluvial deposits and sedimentary rocks, significantly contributes to an elevated earthquake risk, potentially exacerbating structural damage. The Horizontal-to-Vertical Spectral Ratio (HVSR) method, combined with HVSR curve inversion, is employed to analyze seismic parameters. Key parameters include dominant frequency, amplification factor, seismic vulnerability index, ground shear strain, shear wave velocity at a depth of 30 meters (Vs30), and sediment layer thickness. These parameters provide a detailed understanding of the subsurface structure and the region's vulnerability to seismic activity. The results reveal variations in dominant frequency values from 0.3042 Hz to 15.09 Hz, amplification factors from 1.524 to 12.55, seismic vulnerability indices from 0.2 to 376.1, ground shear strain from 9.903×10^{-6} to 1.778×10^{-2}, Vs30 from 42.77 m/s to 764.1 m/s, and sediment layer thickness ranging from 5.838 to 233.4 meters. The findings indicate that the eastern and southeastern parts of the Padaherang Subdistrict are particularly vulnerable to seismic activity, with the potential for cracks, ground subsidence, and other structural deformations. These findings can support regional spatial planning, zoning regulation, and preparedness strategies in high-risk areas.

Keywords: Earthquake; HVSR; Microzonation; Padaherang Subdistrict

1. Introduction

Indonesia, located between the Eurasian, Indo-Australian, and Pacific tectonic plates, experiences significant geological activity. The movement of these plates causes various geological hazards, including earthquakes—sudden ground vibrations caused by the displacement of rock layers within the Earth's crust due to tectonic displacement1). In addition to tectonic causes, earthquakes in Indonesia can also result from volcanic activity, human actions, and the geological characteristics of specific areas. Given the potential for severe economic losses and humanitarian impacts, effective mitigation measures are essential to reduce disaster risks2).

Disaster mitigation involves coordinated efforts before, during, and after an event to minimize risks. Site characterization serves as a powerful tool to evaluate basic seismic risks and identify zones vulnerable to local seismic effects. It provides essential information, including dominant frequency (f_0), site amplification (A_0), and shear wave velocity (Vs), which are crucial for planning strategies to mitigate seismic risks3)–5). Geophysics, a field combining geological and physical sciences, plays a crucial role in understanding subsurface conditions. Microtremor studies are particularly useful in assessing a region's vulnerability to seismic activity, with this research employing the Horizontal-to-Vertical Spectral Ratio (HVSR) method6). This method provides reasonable estimates of the natural frequency of soil, facilitating local microzonation and seismic risk analysis7,8).

Local site conditions significantly influence earthquake

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damage distribution, as they determine how seismic waves are amplified when passing through geological structures. Seismic responses vary due to lateral and vertical heterogeneities in geological settings, which may amplify seismic waves, particularly in areas with thick and soft sediments[9]. The dominant frequency (f_0) and site amplification (A_0) provide insights into the local geological characteristics, with low frequencies indicating thick, soft sediments and high frequencies corresponding to thin, stiff layers. Understanding these parameters is crucial, especially in urban areas where ground shaking can be amplified, increasing the potential for structural damage.

This study focuses on the Padaherang Subdistrict in Pangandaran Regency, West Java Province, a region with seismic potential. While no major active faults pass through this area, its geological conditions—including thick alluvial deposits and sedimentary rocks—necessitate an assessment of earthquake risks. Although Padaherang lacks a direct surface-rupturing fault, it has been historically affected by regional seismic events. The 2006 Pangandaran earthquake and tsunami (Mw 7.7) caused widespread ground shaking in the area. Additionally, several moderate-magnitude earthquakes (M3.5–M5.9) occurred in 2020 and 2021, one of which resulted in structural damage to houses in Padaherang[10]. Data from BPS-Statistics Indonesia indicate that 12 villages in the subdistrict reported earthquake occurrences in 2020, marking an increase from previous years[11]. Based on probabilistic seismic hazard assessments by PVMBG, Padaherang is classified within moderate to high earthquake risk zones due to its proximity to the Sunda subduction zone and surrounding offshore faults[12].Detailed geophysical surveys, including measurements of Vs and sediment layer thickness (h), enhance the accuracy of seismic vulnerability assessments by correlating these parameters with site amplification and natural frequency[13,14]. Mapping seismic vulnerability in Padaherang through the microtremor method is essential to improving disaster mitigation efforts.

Several studies have previously applied the HVSR method to evaluate seismic vulnerability. For example, Yuliatmoko et al[10] conducted a site response analysis in the Padaherang Subdistrict, identifying parameters such as f_0, A_0, K_g. Zuhaera et al[15] investigated shear wave velocity at 30 meters depth (Vs_{30}) in Bandung Regency, while Astuti 1) applied the HVSR method to study local site effects in the Cibeureum Subdistrict of Tasikmalaya City. In addition, Marjiyono and Afnimar[14] used the HVSR method to map geological characteristics in Bandung City (Figure 1).

This research advances previous work by covering the entire Padaherang Subdistrict with 64 measurement points—more than in prior studies. It also incorporates additional parameters, including ground shear strain (γ), shear wave velocity at 30 meters depth (Vs_{30}), and sediment layer thickness (h). These parameters were derived through HVSR curve inversion, a method not applied in earlier studies of the area. Previous works were often limited in spatial coverage, did not utilize HVSR inversion, and did not consider dynamic soil properties. By addressing these limitations, this study provides a more comprehensive seismic assessment, enabling more accurate identification of earthquake hazards and supporting improved mitigation planning in geologically complex regions[16,17]. These insights will contribute to more effective disaster mitigation strategies.

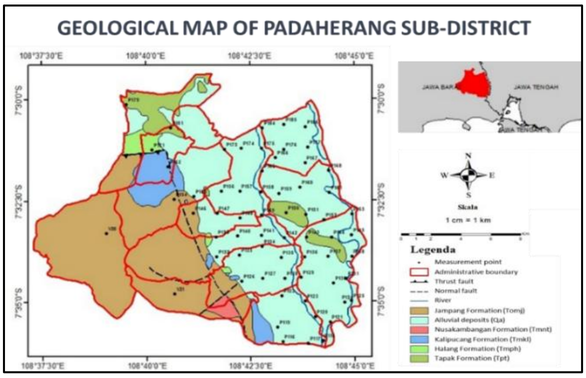

Fig. 1: Geological Map of Padaherang Subdistrict (adapted from: Yuliatmoko et al, 2020)

2. Data and Methods

The microtremor data used in this study were obtained from the Research and Development Center of BMKG during April 2019 in Padaherang Subdistrict. Measurements were conducted using a Lennartz 3D-Lite short-period seismometer, capturing three components of ground motion: North-South horizontal (N-S), East-West horizontal (E-W), and vertical (Z). Each measurement lasted approximately 30 minutes per site. A total of 64 measurement points were selected using a grid-based approach with approximately 1 km spacing between points, ensuring uniform spatial distribution and adequate representation of geological and topographical variability across the subdistrict. This systematic design enhances the spatial reliability and reproducibility of seismic data. Microtremors, which are small ground oscillations influenced by atmospheric phenomena and human activities[18,19]), were analyzed using passive techniques. As microtremors propagate, their elastic waves attenuate due to geometric spreading and inelasticity, especially in non-elastic sediments.

HVSR analysis was conducted following the method proposed by Nogoshi and Igarashi[20,21] and refined by Nakamura[22]. This method provides a reliable estimate of the natural or dominant frequency by analyzing the three microtremor components (N-S, E-W, and Z). The peak amplitude of the HVSR curve reflects subsurface characteristics, such as sediment layers above bedrock, and

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is shaped by both surface and body waves, depending on viscoelastic parameters, source distribution, and distance[23)]. The simplicity of HVSR has made it widely adapted for site effect studies and microzonation mapping in urban areas.

The field data, initially in SEED format, were processed using Geopsy software[24)]. Data processing involved windowing to isolate high-quality signals by excluding transient noise and selecting stable ground motion windows. Fast Fourier Transform (FFT) was applied to convert the data from the time domain to the frequency domain. Smoothing was performed using the Konno-Ohmachi function to prevent infinite values at the H/V peak, ensuring smoother spectral curves[25)]. Parameters such as f_0, A_0, K_g, γ, Vs_{30}, and h were calculated and spatially mapped using Kriging interpolation.

The HVSR curve reveals one or more peaks, with the lowest peak representing the f_0. A higher amplitude at this peak indicates a strong contrast between sedimentary layers and bedrock, which is crucial for assessing seismic vulnerability[26)]. Such characteristics are particularly relevant for regions with thick and soft sediments, where site amplification effects may increase seismic risks[27)].

To further enhance the analysis, HVSR inversion was performed using the ellipticity curve method in Dinver software. The inversion process involved importing the HVSR curve, selecting appropriate model parameters, and executing the model to minimize misfit values, ensuring accurate reflection of geological conditions. The resulting velocity profile was analyzed to extract shear wave velocity (Vs) values at specific depths. These inversion results provide valuable insights into subsurface structures, helping to identify geological boundaries and fault lines[28)]. This methodology ensures accurate imaging of subsurface layers, providing essential data for seismic hazard analysis and urban planning. Passive seismic methods, such as HVSR and inversion techniques, are particularly useful in areas with low to moderate seismicity, as they offer practical insights into ground response and support disaster mitigation efforts[29)].

3. Result and Discussion

The dominant frequency (f0) is a key parameter that reveals the characteristics of subsurface layers, indicating the types of materials presents, such as bedrock (hard layers) and sediments (soft layers). In Padaherang Subdistrict, the analysis of dominant frequency using the Kanai classification yielded values ranging from 0.3042 to 15.09 Hz. The distribution map shows that the subdistrict can be divided into four Kanai classification classes, with low dominant frequency values (<2.5 Hz) in the eastern part, medium values (2.5–6.66 Hz) in the central part, and high values (6.66–20 Hz) in the western part. This correlation suggests that areas with soft lithology are concentrated in the east, while harder lithology is present in the central and western parts. Thus, it can be inferred that the sediment thickness increases in the eastern part and decreases towards the west. Low dominant frequency in the eastern part indicates higher earthquake vulnerability due to the potential resonance of long-period seismic waves, which can lead to wave amplification and increased damage. In contrast, the western part, with higher dominant frequency values, appears more stable and less prone to seismic amplification (Figure 2). These findings provide valuable insights for understanding seismic characteristics and assist in planning effective disaster mitigation strategies.

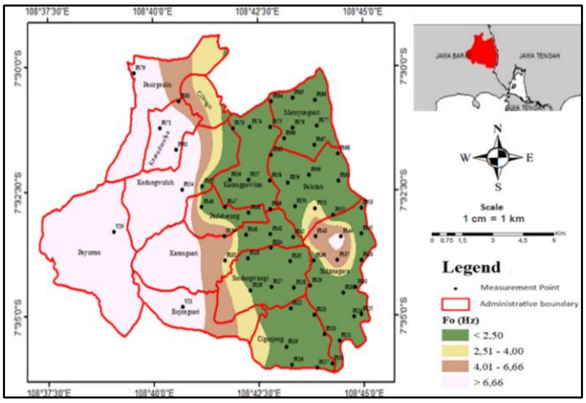

Fig. 2: Map of Dominant Frequency Distribution (fo) in Padaherang Subdistrict

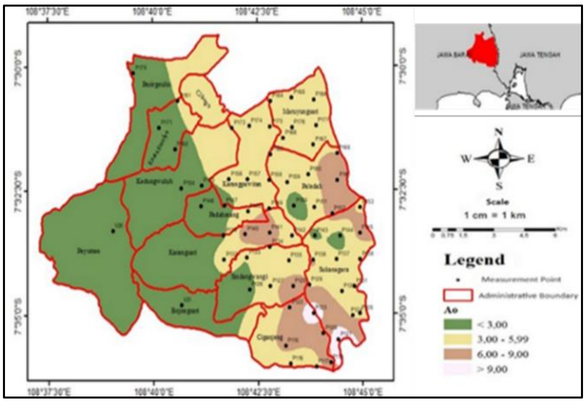

Fig. 3: Map of Amplification factor (A0) in Padaherang Subdistrict

The amplification factor (A0) reflects the strengthening of seismic waves as they pass through soft or hard layers. In Padaherang Subdistrict, amplification factors range from 1.524 to 12.55, with higher values concentrated in the eastern part, gradually decreasing towards the west. The distribution indicates that lowland areas in the east tend to have moderate to high amplification, while highland areas in the west exhibit lower amplification values (Figure 3). A comparison with studies in Mexico City reveals that amplification characteristics can vary significantly with topography[27)]. In Padaherang, areas with thick sediment layers in the lowlands show higher amplification, emphasizing the critical role of geological conditions and dominant frequency. This pattern suggests that the eastern part of the subdistrict, characterized by high amplification, is more vulnerable to earthquake damage, necessitating targeted mitigation efforts.

The seismic vulnerability index (Kg) in Padaherang Subdistrict ranges from 0.2 to 376.1, influenced by both amplification factors and dominant frequency. The distribution map indicates that areas in the east and southeast exhibit higher vulnerability, while the western part shows lower values (Figure 4). This pattern aligns with findings from a study in San Francisco, which demonstrated a correlation between seismic vulnerability and post-earthquake damage[30)]. Similar correlations between surface geology and vulnerability were also observed in other regions of Indonesia, where gravity-based subsurface modeling and geological mapping revealed structural controls on seismic response, particularly in fault-prone areas[29,30)]. In Padaherang, lowland areas near the coast with higher vulnerability indices are at greater risk of severe damage, while highland areas with lower indices are less likely to experience significant impacts. This analysis reinforces the need for heightened preparedness in the eastern and southeastern parts of the subdistrict, particularly in lowland areas

The ground shear strain (γ), which measures the soil's deformation capacity under seismic stress, provides further insights into the dynamic response of the region. Ground shear strain values in Padaherang range from 9.903×10^{-6} to 1.778×10^{-2}, with the highest values observed in the eastern and southeastern parts (Figure 5). These areas are prone to phenomena such as soil cracking, subsidence, and elasto-plastic behavior under repetitive stress[31,32)]. In contrast, the central and western parts show lower shear strain values, indicating greater soil stability. This pattern underscores the higher deformation potential in the eastern part, calling for specific attention in disaster mitigation strategies.

The shear wave velocity (Vs_{30}) at a depth of 30 meters, obtained through HVSR curve inversion using the ellipticity curve method, ranges from 42.77 to 764.1 m/s. The distribution map shows lower Vs_{30} values in the eastern part, with values increasing towards the west (Figure 6.a). Based on soil classification according to SNI 1726:2012 (BSN, 2012), the eastern part is dominated by soft soil (SE), the central part by medium soil (SD), and the western part by hard soil to soft rock (SC) and even rock (SB). This classification indicates that the eastern part is more susceptible to seismic wave amplification. A comparison with Vs_{30} data from the USGS (Figure 6.b) shows a similar pattern, with highland areas exhibiting higher Vs_{30} values than lowlands. Although both microtremor and USGS data reveal consistent trends,

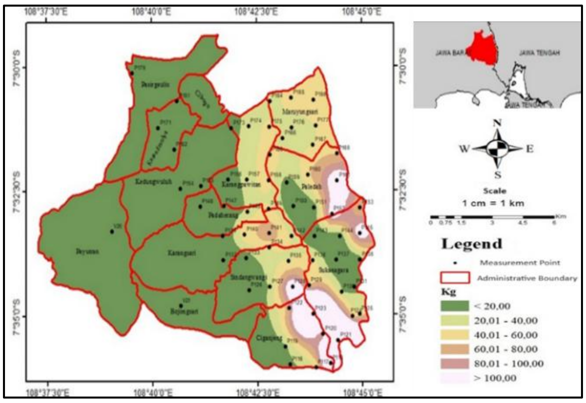

Fig. 4: Map of Seismic vulnerability (Kg) in Padaherang Subdistrict

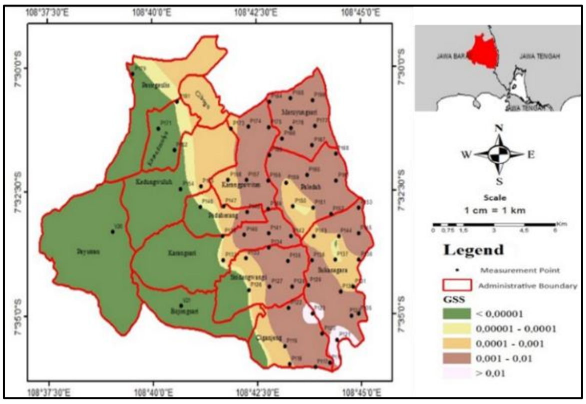

Fig. 5: Map of Ground shear strain (γ) in Padaherang Subdistrict

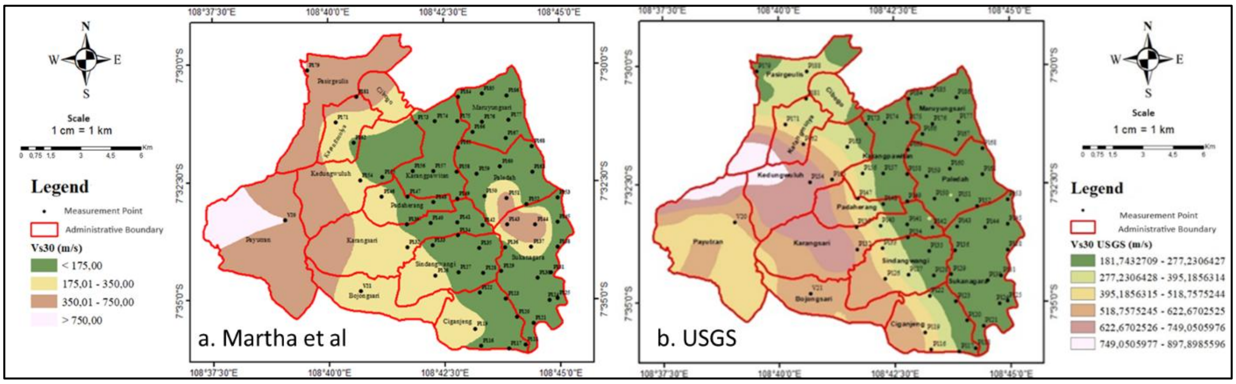

Fig. 6: (a) The map of Shear wave velocity (Vs) values at a depth of 30 meters from the inversion processing and (b) Vs30 Distribution Map by USGS in Padaherang Subdistrict

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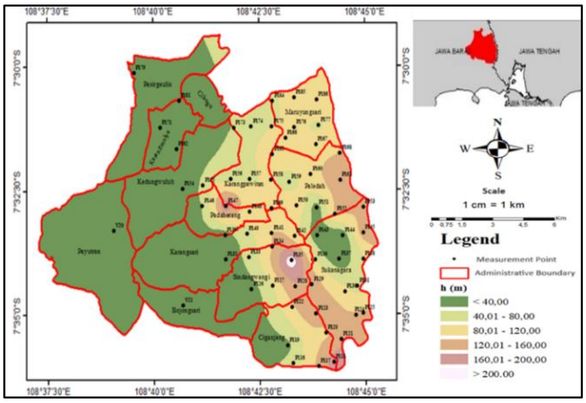

Fig. 7: Map of thickness of sediment layers (h) in Padaherang Subdistrict

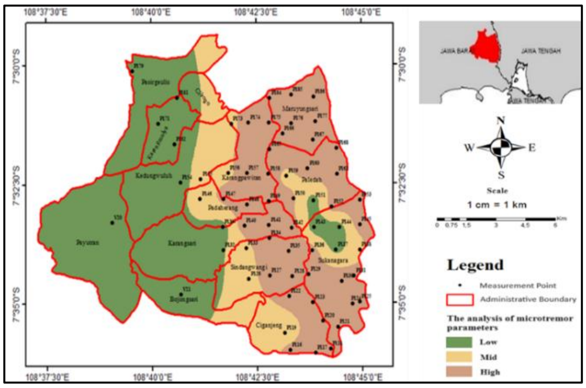

Fig 8. Microzonation Map of Padaherang Subdistrict

microtremor-based measurements provide more detailed insights into the subsurface characteristics. However, it is important to note that HVSR inversion results are subject to uncertainty due to assumptions in the 1D layered model and potential misfits between observed and theoretical ellipticity curves. These uncertainties can affect the accuracy of Vs_{30} estimations, particularly in geologically complex areas. Despite this, the overall fit quality in this study was acceptable for the majority of sites. Future studies may improve reliability by integrating borehole or MASW data for calibration purposes.

The thickness of sediment layers (h), calculated from dominant frequency and shear wave velocity data, ranges from 5.838 to 233.4 meters. The distribution map reveals thicker sediments in the eastern and southeastern parts, exceeding 200 meters, while the western part has thinner layers, often less than 40 meters (Figure 7). This pattern correlates with the region's topography, with lower elevations in the east having thicker sediments and higher elevations in the west having thinner layers. The relationship between sediment thickness, dominant frequency, and shear wave velocity underscores the seismic vulnerability of the eastern part, where soft and thick sediments amplify seismic waves, increasing earthquake risk.

The analysis of microtremor parameters in Padaherang Subdistrict reveals significant correlations among dominant frequency, Vs_{30}, amplification factor, seismic vulnerability index, ground shear strain, and sediment thickness. A comparison between the eastern and western parts highlights distinct seismic characteristics, with the eastern part exhibiting low dominant frequency, low Vs_{30}, and high amplification, while the western part shows the opposite pattern. Specific areas, such as Maruyungsasi, Karangpawitan, Paledah, Sukanagara, Ciganjeng, Sindangwangi, Karangsari, and Padaherang, are identified as having higher earthquake vulnerability. The integration of all microtremor parameters into the microzonation map (Figure 8) indicates that these areas require heightened awareness and preparedness to mitigate the potential impacts of future seismic events.

4. Conclusions

This study provides a detailed assessment of seismic vulnerability in Padaherang Subdistrict through microzonation using the microtremor method. Analysis of HVSR and its inversion yielded key parameters, including dominant frequency, amplification factor, seismic vulnerability index, ground shear strain, Vs_{30}, and sediment thickness. The results indicate that the eastern and southeastern areas—particularly Maruyungsasi, Karangpawitan, Paledah, and surrounding villages—are more susceptible to earthquake impacts, characterized by high amplification and deformation potential. By integrating multiple microtremor-derived parameters, this study contributes a comprehensive and site-specific seismic microzonation map for a region that has not been extensively studied before. The approach enhances the understanding of local site effects and subsurface conditions, which are critical for accurate earthquake hazard assessment. These findings can support evidence-based planning for disaster risk reduction, guide land-use regulations, and inform the development of resilient infrastructure in earthquake-prone areas. These findings can support land-use regulation, guide infrastructure development in safe zones, and inform disaster response planning by local government agencies and emergency planners in high-risk areas. Moreover, this methodology may serve as a practical reference for similar seismic microzonation efforts in other vulnerable regions with limited ground motion data.

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