Seismic Hazard Analysis Based on Peak Ground Acceleration and Modified Mercalli Intensity in North Bengkulu Regency, Bengkulu Province

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Abstract. North Bengkulu is an earthquake-prone area. Therefore, this study is necessary in this area. This study examines the spatial characteristics of earthquake-related ground shaking in North Bengkulu Regency through the combined evaluation of ground motion parameters and macroseismic intensity indicators. Peak Ground Acceleration (PGA) was estimated using the Kanai approach, incorporating site-specific dynamic properties derived from ambient vibration measurements processed via Horizontal-to-Vertical Spectral Ratio analysis. Key seismological inputs, including earthquake size and source proximity, were extracted from global seismic catalogs maintained by international monitoring agencies for events recorded between 1924 and 2024. The results indicate that large portions of the study area experience moderate to relatively strong ground motion, which corresponds to Modified Mercalli Intensity (MMI) levels ranging from VI to IX. These conditions underline the importance of strengthening preparedness and mitigation strategies in sectors exhibiting elevated seismic vulnerability in order to limit potential impacts from future earthquakes.

Keywords: Seismic hazard, PGA, MMI, HVSR method, disaster.

1 Introduction

North Bengkulu Regency, located in Bengkulu Province, is situated within a geodynamically active environment that predisposes the region to significant seismic disturbance. This condition is primarily governed by its position adjacent to a major plate boundary system operating

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offshore, where large-scale lithospheric interactions dominate regional deformation patterns. Beyond subduction-controlled mechanisms, onshore tectonic deformation is further shaped by the Sumatran Fault System, particularly the Ketahun segment, which extends across the study area [1–2].

Geophysical studies have shown that the southern sector of Sumatra Island, encompassing North Bengkulu, is characterized by pronounced tectonic loading manifested through elevated strain accumulation and energy release. Such conditions promote repeated fault activity and result in a higher rate of seismic occurrences compared with other regions of the island [2–4]. Seismic records document several major events associated with these processes, including large-magnitude earthquakes in 2000 and 2007 (Mw 7.9 and 8.4, respectively). Additional significant earthquakes linked to displacement along the Ketahun fault segment were recorded in 1943 and 1952, with magnitudes of 7.3 and 6.8, respectively [4-6].

As a region undergoing active development, North Bengkulu Regency necessitates robust spatial insight into earthquake-related hazard variability to inform planning strategies grounded in risk awareness. Distinguishing areas with differing levels of seismic threat is essential for reducing potential damage and strengthening disaster preparedness measures. Within this framework, the present study characterizes seismic hazard conditions across the study area through the application of ground-motion and intensity-based indicators, namely Peak Ground Acceleration (PGA) and Modified Mercalli Intensity (MMI).

Previous research on seismic hazard analysis in this area was conducted partially in coastal areas, for example at Urai and Nangai beaches, using shear waves [7,8]. Meanwhile, Budi et al. [9] used PGA parameters in North Bengkulu, but with a spatial approach that was still too broad using 29 microtremor measurement points. Thus, this study provides novelty in terms of completeness of microzonation data and is more comprehensive.

2 Method

This investigation combines site-based observations with auxiliary seismological records. Field observations consist of ambient ground-motion measurements analyzed using the Horizontal-to-Vertical Spectral Ratio technique, while supporting data were obtained from global earthquake catalogs maintained by international seismic monitoring agencies. A total of 247 HVSR measurement locations were distributed throughout the study area (**Figure 1**). The seismic dataset includes shallow-focus events (depth < 50 km) with moment magnitudes of Mw ≥ 5 recorded over a century-long interval from 1924 to 2024. For each event, source characteristics such as event magnitude and source-to-site distance were determined and subsequently utilized in the analytical procedure.

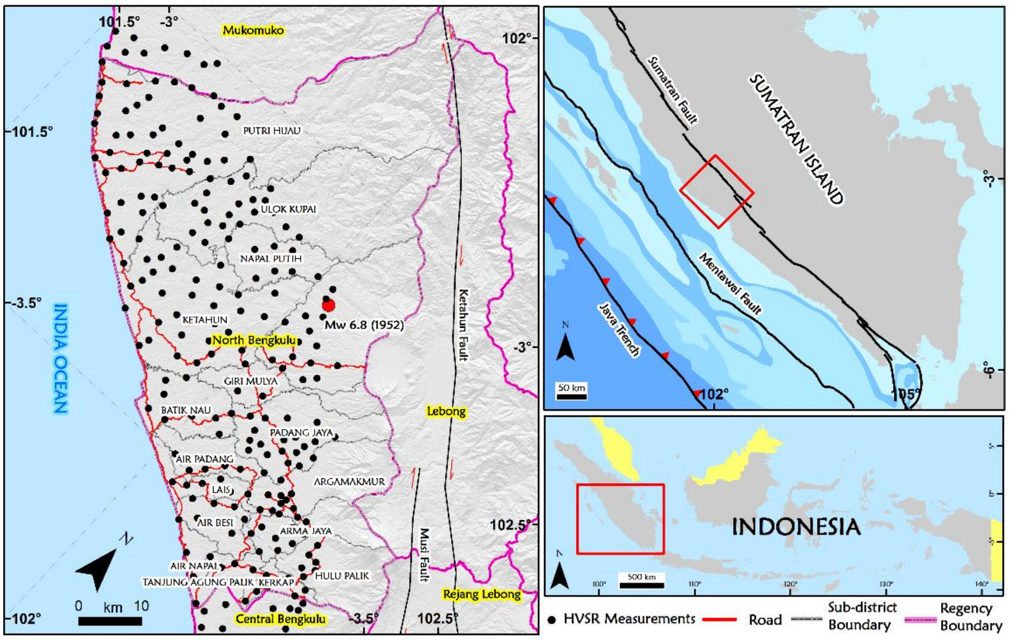

Fig. 1. Spatial distribution of HVSR observation sites across North Bengkulu Regency, Bengkulu Province. The map also illustrates the offshore subduction system and the onshore trace of the Sumatran Fault.

Ambient vibration data were recorded at 247 locations using a PASI Gemini-2 portable broadband seismometer equipped with a triaxial sensor, following the procedures recommended in the Site Effects Assessment using Ambient Excitation (SESAME) framework [10]. Each measurement was performed with a recording duration of 30 minutes. The HVSR processing produces a dominant site frequency, which was subsequently converted into the corresponding predominant soil period. The resulting site-period values were integrated with seismic source characteristics obtained from earthquake catalogs, including moment magnitude and source-to-site separation distance. These parameters were then introduced into equation (1) to derive peak ground acceleration (PGA) values [11].

$$\alpha = \frac{5}{\sqrt{T_G}} 10^{0,61 M_w - 1,66\, log_{10} R - \frac{3,60}{R} log_{10} R + 0,167 - \frac{1,83}{R}}, \quad (1)$$

where T_G denotes the predominant soil period (s), Rrefers to the minimum distance between the seismic source and the measurement location (km), and $M_w$represents the moment magnitude. Following the computation of PGA, Modified Mercalli Intensity (I_{mm}) values were estimated at each site using the empirical relationship given in equation (2) [12]:

$$I_{mm} = 3,66\, log(\alpha) - 1,66. \quad (2)$$

The derived PGA and MMI parameters were subsequently used to evaluate seismic hazard conditions across North Bengkulu Regency, Bengkulu Province. The level of earthquake risk based on the PGA value and MMI scale according to the Meteorology, Climatology, and Geophysics Agency (BMKG) [13,14].

3 Results and discussion

Ambient vibration measurements collected from 247 HVSR survey locations provide uniform spatial coverage of the study area. Data acquisition was performed with a sampling interval of 5 ms, corresponding to a sampling frequency of 200 Hz, and each recording lasted 30 minutes. According to the Nyquist criterion, the usable frequency content of the recorded signals extends between 0.5 and 20 Hz. Representative waveforms obtained from the HVSR survey are illustrated in **Figure 2**. The unprocessed records exhibit transient, high-amplitude disturbances that originate from non-seismic sources. Such disturbances were removed during data preparation to isolate ambient ground motion of natural origin. These transient signals are commonly associated with industrial operations, vehicular traffic, and other anthropogenic activities and may affect all three motion components (horizontal and vertical) of the recorded data [15–18]**.**

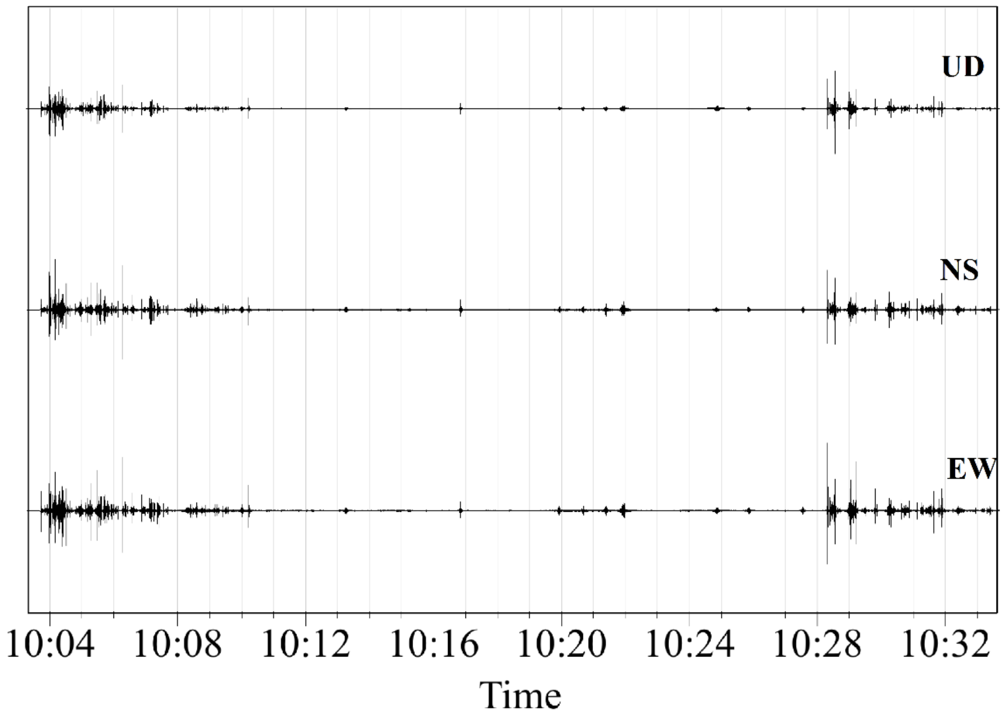

Fig. 2. Representative ambient ground-motion waveforms obtained from HVSR field observations, showing microtremor signals recorded along orthogonal horizontal and vertical components.

Following signal conditioning, HVSR-derived site parameters were obtained, including the dominant site frequency (f_0) and the associated amplification factor (A_0). These parameters were subjected to quality control procedures in accordance with the Site Effects Assessment using Ambient Excitation framework [10]. All datasets satisfied the prescribed reliability requirements. Examples of f_0 and A_0 values at selected observation sites are presented in **Figure**

3. In the subsequent seismic hazard analysis, only the dominant f_0 was considered, whereas the A_0 was excluded. The extracted f_0 values span a range from 0.77 to 14.26 Hz and were converted into corresponding site periods (T_g). The derived site-period information was integrated with seismic source characteristics, including moment magnitude and source-to-site distance obtained from earthquake catalog data, to estimate PGA using equation (1). The resulting PGA values were then used to calculate MMI through equation (2). Spatial distributions of both PGA and MMI across the study area are presented in **Figure 4**.

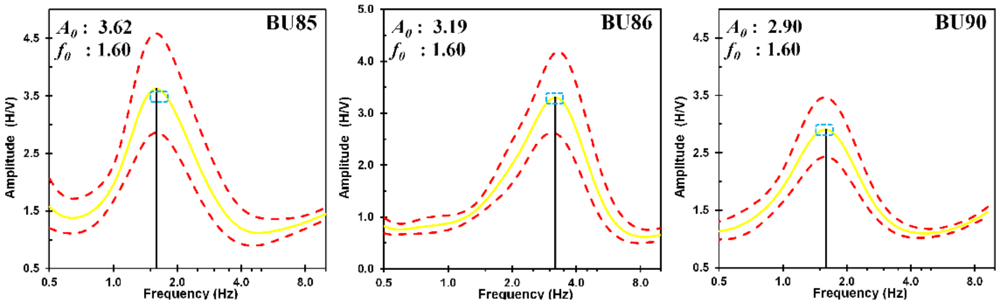

Fig. 3. Representative HVSR results illustrating amplification factor (A_0) and dominant site frequency (f_0) at selected measurement locations. Station BU85 exhibits an A_0 value of 3.62 with an f_0 of 1.60 Hz, station BU86 shows an A_0 of 3.19 with an f_0 of 1.60 Hz, and station BU90 records an A_0 of 2.90 with an f_0 of 1.60 Hz.

The estimated PGA values across the study area vary between 0.15 g and 0.66 g, while the associated MMI levels correspond to intensity grades ranging from VI to IX. The first zone, on the VI to VII MMI scale, has a PGA ranging from 0.092 to 0.34. The second zone, on the VII to VIII MMI scale, has a PGA ranging from 0.34 to 0.65. The third zone, on the VIII to IX MMI scale, has a PGA ranging from 0.65 to 1.24 [19]. PGA characterizes the maximum ground motion induced by seismic events at a given location [10], with increasing values reflecting progressively higher levels of seismic hazard and structural risk. The majority of the study area falls within the moderate hazard classification; however, several zones, including the Giri Mulya sub-district, are identified as areas of elevated seismic hazard. High-hazard zones are predominantly associated with unconsolidated alluvial deposits composed of boulders, gravel, sand, silt, mud, and clay, as well as with lithological units of the Bintunan Formation. This formation is characterized by polymict conglomerates, breccias, reef limestone, tuffaceous claystone, pumice-rich materials, and silicified wood lithologies [21,22], which collectively contribute to increased ground motion amplification under seismic loading.

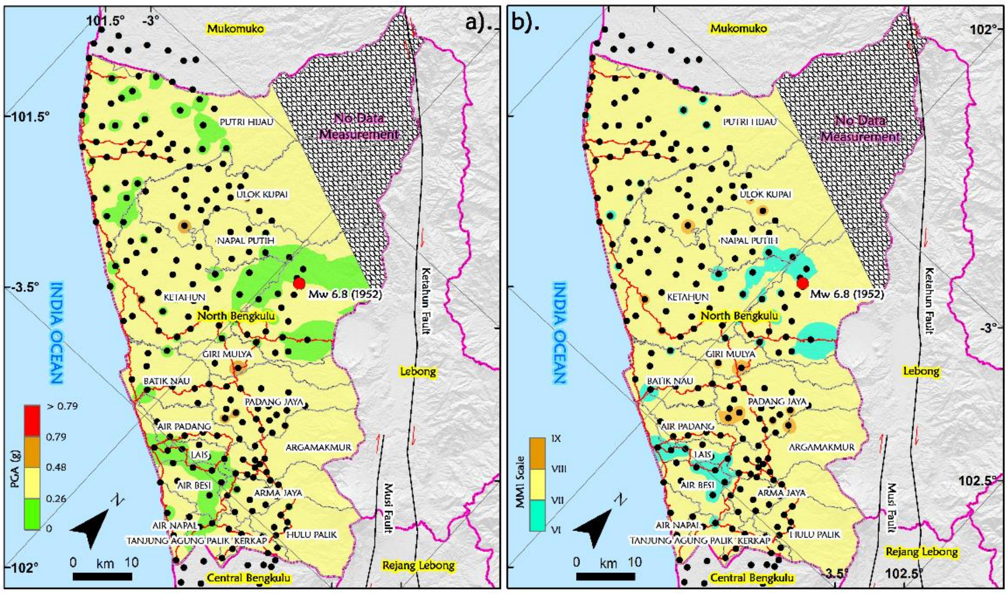

Fig. 4. Distribution map of PGA values using the Kanai formula and MMI scale in North Bengkulu regency, Bengkulu Province.

Previous investigations support these findings. Sesilia et al. [23] reported that the Urai Village in the Ketahun sub-district has experienced widespread abrasion due to soft soil lithologies that are highly susceptible to seismic loading. Similarly, Farid et al. [24] demonstrated that areas characterized by high PGA values exhibit significant coastal abrasion, with an average shoreline retreat of approximately 1.5 m/year. The results also indicate a strong relationship between PGA and MMI, whereby increasing PGA values correspond to higher MMI levels. In the study area, MMI values ranging from VI to IX reflect a wide spectrum of seismic impacts, including vibrations felt by all residents, falling wall plaster, damaged industrial chimneys, light structural damage to well-constructed buildings, cracking or partial collapse of poorly constructed structures, overturned heavy furniture, collapsed monuments, and, in extreme cases, severe damage to reinforced buildings and displacement of structures from their foundations [19]. Consequently, heightened vigilance and mitigation efforts are essential in areas exhibiting high PGA and MMI values to reduce potential seismic impacts within the study area.

4 Conclusion

This study presents a spatial assessment of seismic hazard variability across North Bengkulu Regency, Bengkulu Province, highlighting areas characterized by differing levels of earthquake risk. Locations exhibiting elevated seismic hazard levels require prioritized attention to minimize potential impacts on local communities, particularly in zones dominated by unconsolidated or soft sedimentary deposits. The outcomes of this research may serve as a scientific basis for local authorities and related stakeholders in formulating regional development policies that incorporate disaster risk reduction measures while considering local contextual conditions. To improve the reliability and completeness of seismic hazard evaluations, future research integrating additional geophysical and geotechnical parameters is strongly encouraged.

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