

Mapping Seismic Vulnerability Index and Vs30 Based on 1D MASW in Lempuing Subdistrict, Bengkulu City

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Abstract

Bengkulu City lies at the convergence of the Indo-Australian and Eurasian plates, flanked by the Mentawai and Semangko faults, making it one of Indonesia's most seismically hazardous regions. Although Lempuing Subdistrict suffered severe liquefaction during the 2007 Mw 8.4 earthquake, subdistrict-scale seismic site characterization remains lacking, as existing studies rely mainly on indirect microtremor/HVSR measurements. This study addresses that gap by applying 1D MASW at 20 points across Lempuing, inverting Rayleigh wave dispersion curves to obtain shear-wave velocity profiles to 30 m depth, from which Vs30, dominant frequency (f_0), amplification factor (A_g), and vulnerability index (K_g) were derived and mapped spatially. Vs30 values (287.52–573.23 m/s) place the area within NEHRP classes C–D, with higher velocities and shallower bedrock near the coastline reflecting denser littoral deposits. This shallow, compact subsurface corresponds to higher dominant frequencies (2.3–4.7 Hz), low amplification (1.03–1.87), and low-to-moderate vulnerability ($K_g = 0.2$ –1.4), showing these parameters are mechanistically coupled. Lempuing's subsurface appears more compact and less deformation-prone than soft-sediment areas elsewhere in Bengkulu, though comparison warrants caution given differing methods. This study offers the first MASW-derived, multi-parameter microzonation dataset at the subdistrict scale, with implications for seismic design and land-use planning.

Kata Kunci: 1D MASW; Vs30; amplification factor; seismic vulnerability index; Lempuing Subdistrict

INTRODUCTION

Bengkulu Province is situated along the convergent boundary between the Indo-Australian and Eurasian plates and is strongly influenced by the Mentawai subduction zone and the Semangko Fault, making it one of the regions with the highest seismic hazard in Indonesia (Harlianto & Muhamad, 2018). This hazard was manifested in the moment magnitude (Mw) 8.4 earthquake that occurred on September 12, 2007 (BMKG, 2010), which triggered widespread liquefaction and structural damage in Lempuing District (Refrizon et al., 2013), thereby underscoring the urgent need for

detailed seismic site characterization in the area.

Locally, Bengkulu City is underlain by unconsolidated Quaternary alluvial terrace deposits (Qat) and shallow groundwater conditions that amplify near-surface site effects. Locally, Bengkulu City is predominantly underlain by unconsolidated Quaternary alluvial terrace deposits (Qat) and characterized by shallow groundwater conditions, both of which contribute to significant seismic site amplification (Sugianto et al., 2017; Vikki et al., 2022; Mase et al., 2021a). A previous MASW survey in Lempuing

confirmed that the shallow subsurface consists predominantly of soft-to-medium sand and clay layers susceptible to seismic wave amplification (Angglena et al., 2022), thereby confirming the area's susceptibility to earthquake-induced ground deformation

Site response is conventionally evaluated through three parameters: the time-averaged shear-wave velocity to 30 m depth (V_{s30}), the international basis for site classification (BSSC, 2020; ICC, 2021; BSN, 2019); the amplification factor (A_g), reflecting the impedance contrast between soil and bedrock; and the seismic vulnerability index ($K_g = A_g^2/f_0$), which integrates amplification and resonance frequency into a single deformation-susceptibility proxy (Nakamura, 2000). Because amplification can vary sharply over short distances even within similar tectonic settings (Maheswari et al., 2010), relying on any single parameter risks misrepresenting the actual spatial distribution of seismic hazard. An integrated approach combining V_{s30} , A_g , and K_g is therefore essential to delineate earthquake-prone areas at a resolution suitable for hazard mitigation. (Fitri et al., 2018).

Despite the well-documented liquefaction hazard, previous investigations in Lempuing have been limited to preliminary near-surface geophysical and hydrogeological studies (Angglena et al., 2022), leaving the area without a spatially resolved, subdistrict-scale dataset that integrates V_{s30} , A_g , and K_g for comprehensive seismic site characterization. This represents a significant limitation because previous microzonation studies across Bengkulu (e.g., Fitri et al., 2018, in coastal Bengkulu; Hadi et al., 2024, in South Bengkulu Regency; Hadi, 2025, in Selebar Subdistrict; Anggi et al., 2025, in Central Bengkulu) have relied primarily on microtremor/HVSR methods, which infer site response from ambient vibrations rather than direct

measurements of shear-wave velocity, thereby providing only limited constraints on subsurface stratigraphy. More importantly, no previous study has focused specifically on Lempuing while integrating a high-resolution multichannel surface-wave dataset with comprehensive subdistrict-scale mapping of V_{s30} , A_g , and K_g for seismic site characterization. This highlights a clear and unresolved gap: the spatial pattern of seismic vulnerability within the subdistrict that experienced the most severe liquefaction during the 2007 earthquake remains poorly understood..

To address this knowledge gap, this study employs one-dimensional Multichannel Analysis of Surface Waves (1D MASW) at 20 strategically distributed measurement points across Lempuing Subdistrict to characterize the shallow subsurface and derive spatially continuous seismic site parameters.. Unlike the ambient-noise-based microtremor methods employed in previous Bengkulu microzonation studies, MASW directly characterizes the subsurface shear-wave velocity structure through active-source Rayleigh-wave dispersion analysis (Park et al., 1999; Socco & Strobbia, 2004). This approach provides improved depth constraints on the V_s profile and enables V_{s30} , A_g , and K_g to be derived from a single internally consistent dataset, eliminating the need to combine multiple indirect proxies. The novelty of this study is twofold. First, it presents the first integrated, multi-parameter seismic microzonation of Lempuing Subdistrict by jointly mapping V_{s30} , A_g , and K_g from a single MASW dataset. Second, it demonstrates the advantages of a MASW-based approach over the microtremor-based methods commonly adopted in regional studies, providing a transferable methodological framework for seismic microzonation in other liquefaction-prone coastal subdistricts of western Sumatra. The resulting V_{s30} , A_g , and K_g maps provide

an evidence-based foundation for earthquake-resistant structural design, land-use planning, and disaster risk mitigation in Lempuing, while offering a transferable framework for seismic microzonation in similar liquefaction-prone coastal environments

MATERIALS AND METHOD

The research site is located in Lempuing Subdistrict, Ratu Agung District, Bengkulu City, and the locations of the measurement points throughout the study area are shown in Figure 1. The one-dimensional Multichannel Analysis of Surface Waves (1D MASW) method was selected instead of passive ambient-noise techniques, such as microtremor/HVSR, because its active-source, multichannel acquisition directly estimates the subsurface shear-wave velocity structure through Rayleigh-wave dispersion analysis. This approach provides improved depth constraints for Vs30 estimation compared with resonance-based methods, making it particularly suitable for the integrated seismic

microzonation framework adopted in this study. Unlike invasive subsurface investigation methods, MASW is non-destructive and well suited to the densely developed urban and peri-urban environments of Lempuing, where borehole investigations are logistically challenging. The one-dimensional MASW approach was specifically adopted because each measurement point yields an independent vertical Vs profile, thereby enabling the generation of spatially distributed datasets across the subdistrict. (Park et al., 1999; Socco & Strobbia, 2004). Data acquisition was carried out using a PASI 16S24-P seismograph connected to a linear array of 24 vertical component geophones with a uniform inter-geophone spacing of 2 meters, giving an active spread length of 46 meters per measurement point. Seismic energy was generated using a sledgehammer source, with the impact point (shot location) positioned 4 meters from the first geophone to ensure adequate excitation of the surface-wave energy across the frequency range required for shallow Vs profiling.

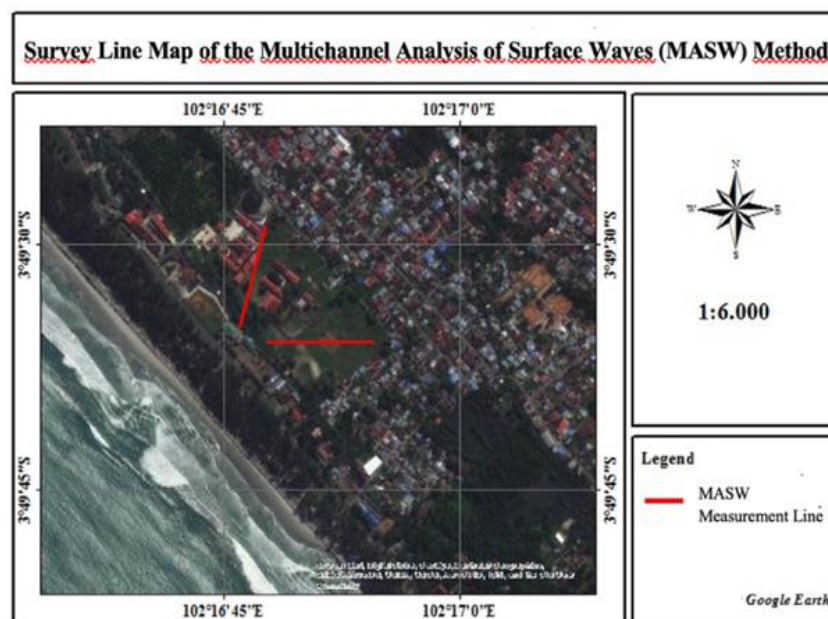


Figure 1. Map of 1D MASW Survey Locations

To improve the signal-to-noise ratio under field conditions, which was particularly important because of the relatively high ambient noise levels in this populated subdistrict, multiple hammer blows were vertically stacked at each measurement point. The number of stacks was increased as needed until stable and repeatable waveforms were achieved before the record was finalized. A total of 20 measurement points were distributed across the study area, with their density and spacing optimized to balance two competing requirements: representative coverage of Lempuing's two principal geomorphological zones (the immediate coastal strip and the inland alluvial plain) and operational feasibility in a densely settled urban subdistrict, where unrestricted survey-line deployment was not always possible. Within these constraints, points were positioned to avoid spatial redundancy while ensuring that no major zone of the subdistrict particularly areas previously affected by liquefaction during the 2007 earthquake (Refrizon et al., 2013) was left uncharacterized; the resulting layout is shown in Figure 1. The recorded seismic data from each point were processed using WinMASW 5.0 software. Data processing began with the extraction of the dispersion curve, which describes the relationship between phase velocity and frequency, from each multichannel record using frequency-domain transformation with the f - k or phase-shift method. The fundamental mode of Rayleigh-wave dispersion was manually identified and picked over the resolvable frequency range, as the fundamental mode typically exhibits the highest energy and can be identified more reliably from near-surface MASW data (Park et al., 1999).

The picked dispersion curves were then used as input for one dimensional, layered-earth inversion to recover the shear wave velocity (V_s) profile with depth. Forward dispersion curves were

computed for a multilayer model and compared with the observed (picked) curve; the layer V_s values, thicknesses, and (for the deepest layer) half space velocity were then updated iteratively through a least squares scheme that minimizes the difference between observed and modeled phase velocities at each frequency, following standard surface wave inversion procedures (Socco & Strobbia, 2004). An initial subsurface model was established for each measurement point based on the expected stratigraphy of Lempuing's alluvial deposits, with compressional wave velocity and density constrained within physically realistic ranges and Poisson's ratio fixed at a value typical of saturated unconsolidated sediments; the number of layers and total depth range were set to ensure adequate resolution of the upper 30 m, consistent with the V_{s30} computation requirement. Inversion was iterated until convergence, defined as no further reduction in misfit between successive iterations. Inversion quality at each point was then evaluated quantitatively using the root mean square error (RMSE) between the observed and modeled dispersion curves, expressed as a percentage misfit. Only inversion results with an RMSE below the acceptance threshold (generally under 10%, consistent with common practice in surface-wave inversion; Socco & Strobbia, 2004) were retained for subsequent analysis. The points exceeding this threshold were reexamined by adjusting the initial model or re-picking the dispersion curve, and, where the misfit remained unacceptably high, the point was reacquired in the field. From the accepted V_s profiles, three key site characterization parameters were then derived. First, the time-averaged shear wave velocity to 30 meters depth (V_{s30}) was computed at each point using the standard harmonic-mean formula defined by NEHRP (BSSC, 2020), expressed as:

$$Vs_{30} = \frac{30}{\sum \frac{d_i}{V_{si}}}$$

where d_i is the thickness and V_{si} is the shear wave velocity of the i -th layer within the upper 30 m. Site classification was then assigned to each point based on both the NEHRP/IBC criteria (BSSC, 2020; ICC, 2021) and the Indonesian Seismic Design Standard SNI 1726:2019 (BSN, 2019), which adopt the same Vs_{30} thresholds. Second, the amplification factor (Ag) was estimated empirically from the Vs_{30} value at each point using the regression relationship proposed by Fujimoto and Midorikawa (2006), expressed as:

$$\log(Ag) = 2.367 - 0.852 \log(Vs_{30})$$

where Vs_{30} is the time-averaged shear-wave velocity to 30 m depth (m/s) obtained from Equation (1) above, and Ag is the resulting amplification factor. This empirical regression was derived by Fujimoto and Midorikawa (2006) from a large strong-motion dataset and directly links the amplification potential of near-surface soils to Vs_{30} , allowing Ag to be computed consistently at every point from the same Vs profile used for site classification, without requiring independent density or layering assumptions. The amplification interpretation embedded in this formulation is consistent with the general impedance-contrast principle described by Nakamura (1997, 2000): a lower Vs_{30} (a softer surface layer relative to bedrock) yields a higher Ag value, reflecting greater potential for seismic-wave strengthening near the surface. Third, the dominant frequency (f_0) was estimated from the same Vs profile using the quarter-wavelength approximation, following the relationship

$$f_0 = \frac{Vs}{4H}$$

where H is the thickness of the soft soil layer and Vs is the representative shear wave velocity of that layer (Nakamura, 2000). Finally, the seismic vulnerability index (Kg) was calculated at each point using the formulation proposed by Nakamura (2000):

$$Kg = \frac{Ag^2}{f_0}$$

This index captures the combined effect of soil amplification potential and resonance frequency, and has been widely adopted as a proxy for the susceptibility of near-surface soils to earthquake-induced deformation (Daryono et al., 2009; Refrizon et al., 2013). All three parameters Vs_{30} , Ag , and Kg obtained at the 20 discrete measurement points were subsequently interpolated onto a continuous grid and visualized as two-dimensional (2D) spatial distribution maps using the kriging algorithm in Surfer 13. Kriging was selected because, as a geostatistical interpolator, it accounts for the spatial autocorrelation structure among neighboring data points and provides an unbiased, minimum-variance estimate at unsampled locations, making it more representative of gradational subsurface conditions than simpler deterministic interpolators (e.g., inverse distance weighting) when the underlying point distribution is irregular, as in this study. The resulting grids enabled a comprehensive assessment of seismic site conditions across Lempuing Subdistrict.

The interpretation of the derived parameters followed established classification schemes. For Vs_{30} -based site classification, the NEHRP site class criteria as adopted in SNI 1726:2019 (BSN, 2019), NEHRP (BSSC, 2020), and IBC (ICC, 2021) were applied, as summarized in Table 1. The dominant frequency (f_0) is the frequency at which the soil column resonates most strongly and is inversely related to the thickness of

the soft sediment layer thicker, softer deposits tend to produce lower dominant frequencies. The amplification factor (A_g) describes how much the local soil conditions amplify incoming seismic waves relative to the underlying bedrock, with higher values indicating greater amplification potential. Classification of A_g and f_0 values followed the scheme of Daryono et al. (2009), as presented in

Tables 2 and 3. The seismic vulnerability index (K_g), computed as $K_g = A_g^2 / f_0$ following Nakamura (2000), integrates both parameters into a single measure of the susceptibility of the near-surface soil to deformation under seismic loading; higher K_g values indicate zones where ground deformation during earthquake shaking is more likely to occur.

Table 1. Site Class Classification Based on V_{s30} (Wangsadinata, 2006).

Site Class	Soil Type	V_s (m/s)
A	Hard rock	> 1500
B	Medium rock	$750 < V_s \leq 1500$
C	Very dense soil and soft rock	$350 < V_s \leq 750$
D	Stiff soil	$175 < V_s \leq 350$
E	Soft soil	≤ 175

Table 2. Classification of Dominant Frequency (f_0).

Zone	Dominant Frequency (Hz)	Classification
1	6,67 – 20	Tertiary or older rock (hard sand, gravel, etc.)
2	4 – 6,67	Alluvial deposits with thickness of 5 m (sand-gravel, sand, hard clay, loam, etc.)
3	2,5 - 4	Alluvial deposits with thickness > 5 m, consisting of sand gravel, sand, hard clay, loam, etc.
4	$< 2,5$	Alluvial deposits formed from delta sedimentation, topsoil, and mud, with a thickness of 30 m or more.

Table 3. Classification of Amplification Factor (A_g).

Zone	Amplification Factor (A_g)	Classification
1	< 3	Low
2	$3 \leq A_g \leq 6$	Medium
3	$6 \leq A_g \leq 9$	High
4	> 9	Very High

RESULT AND DISCUSSION

Site Classification Based on Vs30

The Vs profiles obtained at the 20 measurement points (Figure 2) were converted into soil-type classes using the V_s - γ_{sat} relationship in Table 2 and the

site-class criteria in Table 1. The results show that Lempuing Subdistrict is not underlain by a single, uniform soil type: five site classes were identified across the area, namely soft soil, medium soil, very dense soil, soft rock, and hard rock,.

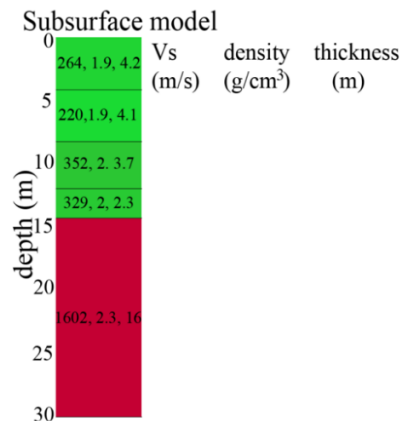


Figure 2. Vs profile with depth.

Table 4. Classification of subsurface layer types based on Vs against γ_{sat}

Point	Layer	Depth (Z) (m)	V_s (m/s)	γ_{sat} (kN/m^3)	Description	Site Class
1.1	1	0 - 4,2	264	19,14	Intact clays	Medium Soil
	2	4,2 - 8,3	220	18,01	Sands	Medium soil
	3	8,3 – 12	352	19,45	Intact clays	Very dense soil and soft rock
	4	12 - 14,3	329	19,08	Sands	Medium soil
	5	Half space	1602	Half space	Half space	Hard Rock

indicating that subsurface stiffness varies from one location to another within the subdistrict

The Vs profile at Point 1.1 (Table 4) shows a non-monotonic shear-wave velocity profile, varying between 220 and 352 m/s in the upper four layers before increasing abruptly to a half-space velocity of 1602 m/s. This pattern reflects an alternation between clay and sand layers at depths of 0 - 14.3 m: the drop in Vs from Layer 1 (264 m/s) to Layer 2 (220 m/s) corresponds to a looser, more compressible sand layer, while the rise in Vs at Layer 3 (352 m/s) reflects a denser, more consolidated clay layer. Such interbedded lithology is typical of the coastal alluvial deposits (Quaternary alluvial terrace/Qat) that dominate

Bengkulu City, formed by alternating fluvial and marine sedimentation. As discussed below, this same interbedding pattern is a key source of the Vs30 variation observed among the observation points.

In general, the time-averaged shear wave velocity to a depth of 30 meters (V_{s30}) in the Lempuing area ranges from 287.52 to 573.23 m/s (Figure 3), placing the subdistrict within the medium soil to very-dense-soil/soft-rock classes. V_{s30} values above 350 m/s are concentrated in the coastal sections facing directly onto the sea, whereas lower values occur at observation points further inland, away from the coastline. This spatial pattern can be attributed to three interacting factors that vary from one observation point to

another. First is the depositional origin of the sediment: coastal points are more strongly influenced by marine and tidal reworking, which tends to deposit and compact coarser, denser material, whereas inland points are dominated by fluvial-alluvial deposits of finer sand, silt, and clay that remain more loosely packed and consequently yield lower V_{s30} . Second is the proportion and arrangement of soft and stiff layers within the upper 30 m: as illustrated by the interbedded clay-sand sequence at Point 1.1 (Table 4), observation points where thicker or more numerous soft, uncemented layers dominate the profile before a competent layer is reached give a lower harmonic-mean V_{s30} , whereas points that reach a dense, consolidated layer or the bedrock half-space at shallower depth give a higher V_{s30} . Third is groundwater condition: several inland parts of Lempuing are prone to flooding and waterlogging (Sugianto et al., 2017; Vikki et al., 2022; Mase et al., 2021a), and a

shallow water table raises pore-water pressure and reduces the effective confining stress of near surface soils, further lowering their stiffness and, in turn, their V_{s30} . Together, these three factors explain why the V_{s30} distribution in Lempuing is not uniform but instead varies systematically with distance from the coastline, subsurface layering, and groundwater condition at each observation point.

Compared with other seismic microzonation studies in the Bengkulu region, the V_{s30} range obtained for Lempuing (287.52–573.23 m/s) is comparable to, but extends to higher values than that reported by Anggi et al. (2025) for Pondok Kelapa Subdistrict in Central Bengkulu (55–465 m/s), where soft-to-medium material with V_{s30} below 200 m/s dominates most measurement points. This indicates that the Lempuing subsurface is generally more compact, consistent with the stronger influence of coastal sedimentation described above.

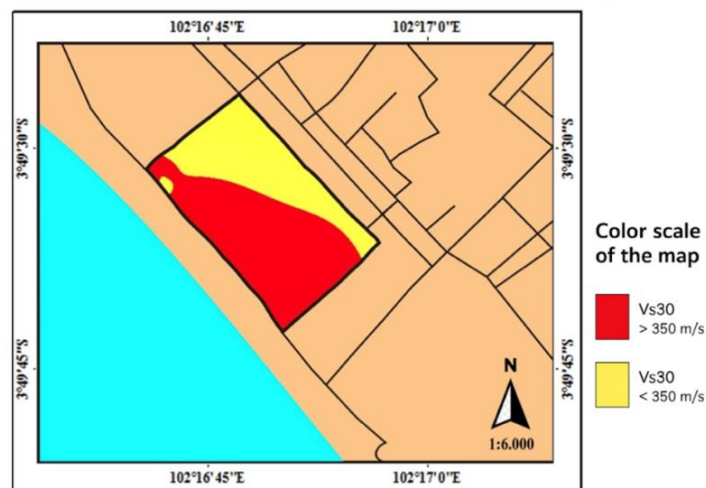


Figure 3. V_{s30} Distribution Map

Dominant Frequency (f_0)

Dominant frequency (f_0) reflects the resonance behavior of the soil column and is governed principally by the thickness and stiffness of the near-surface sediment layer relative to the underlying bedrock: thick, soft deposits produce a

low f_0 , whereas thin, stiff deposits produce a high f_0 (Mucciarelli and Gallipoli, 2004; Sánchez-Sesma et al., 2011). The measured f_0 range of 2.3–4.7 Hz obtained across Lempuing lies well above the very-low-frequency range (below 1 Hz) typically associated with

deep, soft sedimentary basins, indicating a moderately thin sediment column overlying a comparatively shallow engineering bedrock throughout the study area.

Importantly, the spatial pattern of dominant frequency obtained in this study is not an isolated result, but corresponds closely with the V_{s30} distribution and the layered Vs structure described in the preceding subsection. Points situated farther from the coastline, where V_{s30} values approach the lower end of the measured range (approximately 287–350 m/s) and where the inverted Vs profile at Point 1.1 shows a relatively loose, interbedded sand layer within the upper 4–8 m, coincide with the lower dominant

frequencies recorded in this survey (2.3–3.0 Hz). Conversely, points closer to the coastline, where V_{s30} exceeds 350 m/s and the engineering half-space is reached at a comparatively shallow depth of only about 12–14 m, correspond to the higher dominant frequencies (up to 4.7 Hz), consistent with a thinner and stiffer sediment column overlying bedrock. This spatial correspondence confirms that the dominant frequency distribution in Lempuing is a direct expression of the shallow sediment thickness and stiffness contrast already captured by the V_{s30} and Vs profile data, a coupling that has similarly been reported for other shallow coastal microzonation sites in Bengkulu (Mase et al., 2021b; Mase et al., 2024).

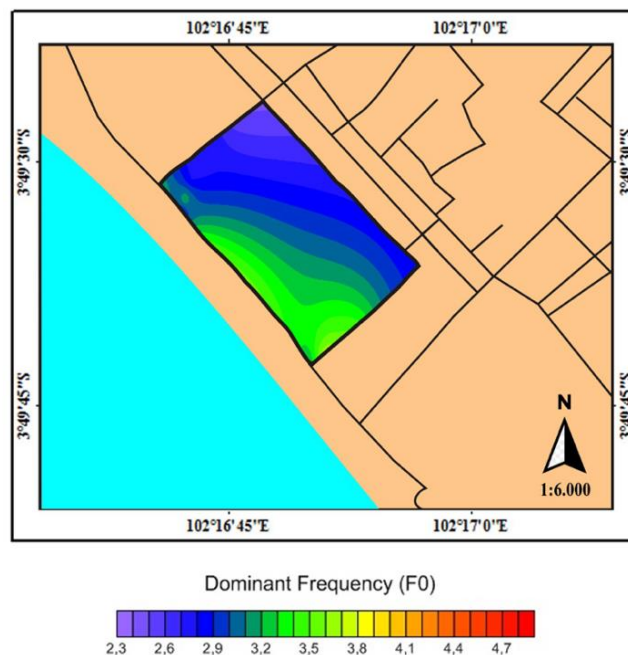


Figure 4. Dominant Frequency (F_0).

Amplification (A_g)

The amplification factor analysis shows that all measurement points in the study area have relatively low amplification values, ranging from 1.03 to 1.87. The distribution of these amplification values is presented in Figure 5. Based on the classification in Table 3, every observation point falls within Zone 1, categorized as a low-amplification

zone. This indicates that the soil layers in the study area have a relatively limited capacity to strengthen seismic waves as they propagate from the bedrock toward the surface. According to Daryono et al. (2009), areas with low amplification values generally have a smaller resonance potential than areas with high amplification values, so that the ground

response to earthquake shaking tends to be more stable.

The amplification factor reflects the impedance contrast between the sediment layer and the underlying bedrock: seismic waves slow down and accumulate energy in soft sediment, producing strong amplification, whereas in denser, stiffer layers the wave-strengthening effect is correspondingly smaller (Daryono et al., 2009). The uniformly low A_g range obtained in Lempuing (1.03–1.87) therefore indicates that the near-surface sediment throughout the study area has a comparatively good degree of compactness, with an impedance contrast against the underlying material that is not large enough to drive substantial amplification of incoming seismic waves.

The amplification factor values for the Lempuing area are relatively low compared with several seismic microzonation results from other parts of Bengkulu. For comparison, Hadi et al. (2024), studying South Bengkulu Regency, reported amplification values (denoted A_0 in that study, equivalent to A_g here) ranging from 1.4 to 3.9, while Hadi (2025), studying Selebar Subdistrict in Bengkulu City, found that most measurement points (56.1%) fell into the medium amplification category, with a small proportion (3.1%) classified as high. The lower amplification values in the Lempuing area relative to these two comparison regions reinforce the indication that the surface soil layer at the study site has a relatively good degree of compactness, consistent with the medium to high V_{s30} values found at most observation points.

This interpretation is further reinforced when the amplification results are examined together with the V_s profile obtained at Point 1.1, where the engineering half-space ($V_s \approx 1602$ m/s) is reached at a shallow depth of only about 12–14 m. Such a rapid, near-surface transition to high-velocity material indicates a relatively small impedance

contrast between the shallow sediment column and the underlying stiffer layer, in contrast to sites elsewhere in Bengkulu where soft sediment persists to much greater depth. Because seismic amplification is governed principally by this velocity contrast between the surface layer and bedrock (Nakamura, 2000), the shallow and moderately compact interbedded sand–clay sequence identified at Lempuing provides a direct physical explanation for why every observation point falls within the low-amplification zone ($A_g < 3$), rather than this result being a coincidental or assumed outcome. This is consistent with recent evidence that V_{s30} alone does not fully determine site amplification, and that the depth to, and sharpness of, the velocity contrast play an equally decisive role in constraining ground response (Mazanec et al., 2024). The joint occurrence of high V_{s30} , shallow engineering bedrock, and low amplification in the present dataset therefore forms a physically coherent picture: the Lempuing subsurface is compact enough, from a comparatively shallow depth, to restrict the trapping and resonant build-up of seismic energy that typically drives strong amplification in thick, soft coastal alluvial deposits (Mase et al., 2021a).

Seismic Vulnerability Index (K_g)

The seismic vulnerability index (K_g) is calculated using the formulation developed by Nakamura (1997), namely $K_g = A_g^2/f_0$, which combines the amplification factor (A_g) and dominant frequency (f_0) obtained from the analysis at each measurement point. This formulation is based on the principle that earthquake damage potential is governed by both the amplification of seismic waves at the ground surface and the resonance characteristics of the soil, represented by its dominant frequency. Consequently, higher K_g values occur when high amplification is associated with low dominant frequency

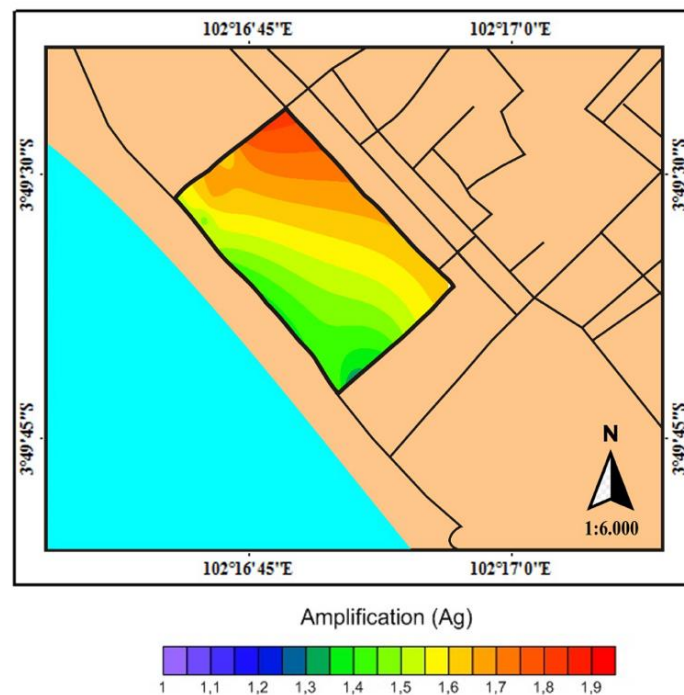


Figure 5. Distribution of Amplification Values (Ag).

It is important to emphasize that V_{s30} , f_0 , A_g , and K_g in this study are not four independent measurements, but four expressions of the same underlying V_s profile obtained through 1D MASW inversion at each point. V_{s30} summarizes the overall stiffness of the upper 30 m; f_0 reflects how that stiffness is distributed with depth, particularly the thickness and velocity of the shallowest soft layer; A_g captures the velocity (impedance) contrast between that shallow layer and the underlying, stiffer material; and K_g combines A_g and f_0 into a single index of ground deformation susceptibility. Because all four parameters are derived from the same subsurface velocity structure, a site with a higher V_{s30} will, by definition, tend to exhibit a thinner soft surface layer, a higher dominant frequency (f_0), a lower seismic impedance contrast, a lower amplification factor (A_g), and consequently a lower seismic vulnerability index (K_g). This internal coupling is precisely the pattern observed in Lempuing: the coastal points with the highest V_{s30} values also show the highest f_0 , the lowest A_g , and the lowest K_g ,

whereas locations farther inland, characterized by comparatively lower V_{s30} values, exhibit lower f_0 , marginally higher A_g , and higher K_g . The coherence of this four-parameter chain across the study area strengthens confidence that the seismic vulnerability pattern reported here reflects genuine subsurface structure rather than measurement scatter or artefacts of the interpolation procedure.

The seismic vulnerability index (K_g) is a parameter used to describe the susceptibility of the surface soil layer to deformation caused by earthquake shaking or ground movement. This parameter reflects the dynamic response of the soil to seismic energy propagating from below the surface toward the ground surface. According to Akkaya (2020), the seismic vulnerability index can be used to assess the stability of soil layers against deformation triggered by seismic activity. Daryono et al. (2009), meanwhile, explain that the seismic vulnerability index value is related to the level of damage that may occur in a region during earthquake shaking. A high K_g value indicates that the surface soil layer is more susceptible

to deformation and damage, whereas a low K_g value indicates relatively more stable ground conditions with a lower degree of vulnerability to seismic activity (Azmiyati et al., 2018). In addition, research conducted by Refrizon et al. (2013) shows that K_g values are closely related to sediment layer thickness, the degree of compactness of the subsurface material, and the characteristics of the bedrock, all of which play a role in determining the extent of damage during an earthquake.

Based on the analysis, the seismic vulnerability index (K_g) values for the study area range from 0.2 to 1.4. The spatial distribution of these values is shown in Figure 6. This range indicates that the study area has a relatively low-to-moderate level of seismic vulnerability. The fact that the K_g values are not particularly large suggests that the surface soil layer in the study area tends to have fairly good stability against deformation caused by earthquake shaking. The potential for damage resulting from local ground conditions is therefore expected to be less significant than in areas with high K_g values.

The seismic vulnerability index combines dominant frequency and amplification factor because low f_0 (thick, soft sediment) together with high A_g produces longer, more strongly amplified ground shaking and, consequently, greater potential for structural damage. In Lempuing, however, the uniformly low A_g values combine with a dominant frequency in the medium range result in low-to-moderate K_g values, indicating that the subsurface is less favorable for the amplification behavior that typically drives high seismic vulnerability in comparable settings.

Several interrelated factors explain why the seismic vulnerability index obtained across the Lempuing subsurface

remains comparatively low. First, the shallow depth to competent material evidenced by the engineering half-space ($V_s \approx 1602$ m/s) intersected at only about 12 - 14 m at Point 1.1, together with the medium-to-high V_{s30} values (287.52 - 573.23 m/s) mapped across the study area limits the thickness of soft, easily deformable sediment available to trap and resonate seismic energy. Second, because K_g is proportional to the square of the amplification factor ($K_g = A_g^2/f_0$), the uniformly low A_g values (1.03–1.87) recorded at every measurement point exert a disproportionately strong dampening effect on K_g that outweighs the influence of the moderate f_0 values (2.3 - 4.7 Hz) in the denominator. Third, the interbedded sand–clay lithology revealed by the inverted V_s profiles, rather than a thick and uniform soft layer, produces alternating stiffness within the shallow sediment column; such heterogeneity tends to interrupt the coherent build-up of resonant energy that typically drives high K_g values in thick, homogeneous soft-soil basins (Refrizon et al., 2013; Daryono et al., 2009). Finally, this pattern is reinforced spatially by the proximity of several measurement points to the coastline, where denser materials contributed by coastal sedimentation raise V_{s30} ; the lowest K_g values in the interpolated map (Figure 6) coincide with the zones of highest V_{s30} and lowest amplification. Collectively, these factors indicate that the low-to-moderate seismic vulnerability index obtained in this study is unlikely to be an artefact of the calculation procedure, but rather reflects a physically consistent outcome of a shallow, moderately compact, and heterogeneously layered subsurface, consistent with the mechanisms broadly comparable to that reported for other relatively stable sedimentary sites along the Bengkulu Coast (Mase et al., 2021b; Mase et al., 2024).

Compared with similar seismic microzonation studies conducted in the Bengkulu region, the seismic vulnerability index obtained for the Lempuing area (0.2 - 1.4) is also relatively low. As a point of comparison, Hadi et al. (2024) reported K_g values ranging from medium-to-high V_{s30} values and low amplification factors (A_g) reinforces the reliability of the present findings, and indicates that seismic vulnerability in the Lempuing area is relatively low, both relative to other reported sites in Bengkulu City and its surroundings. These findings provide an empirical basis that can be used in spatial planning and in setting earthquake disaster mitigation priorities for the Lempuing area and its surrounding region.

Collectively, the four parameters examined in this study describe a single, internally consistent picture of seismic site response in Lempuing Subdistrict. Collectively, the four seismic parameters (V_{s30} , f_0 , A_g , and K_g) provide a coherent and internally consistent characterization of seismic site response in Lempuing Subdistrict. V_{s30} values of 287.52 - 573.23 m/s place most of the area in the medium to hard site classes, with the

0.13 to 2.83 in South Bengkulu Regency, while Hadi (2025) found that the majority of the study area (63.3%) in Selebar Subdistrict fell into the lowest vulnerability category on the scale used in that study. This consistent pattern of low K_g values coinciding with coastal zone approaching soft rock; dominant frequencies of 2.3 - 4.7 Hz indicate a moderately thin, shallow sediment column rather than a deep, soft basin; amplification factors of 1.03–1.87 confirm a limited capacity of the near-surface layers to strengthen incoming seismic waves; and the resulting seismic vulnerability index of 0.2 - 1.4 falls within the low-to-moderate category. None of these parameters, considered alone, would be sufficient to characterize the site; it is the convergence of these parameters toward a stiff, shallow, and only weakly amplifying subsurface that results in a correspondingly low deformation susceptibility and provides a robust basis for concluding that Lempuing Subdistrict currently exhibits a comparatively favourable, though not risk-free, seismic site response relative to other parts of Bengkulu City.

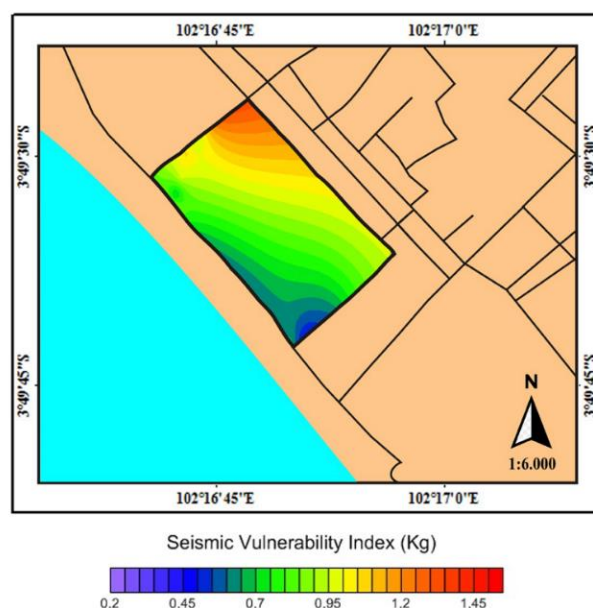


Figure 6. Seismic Vulnerability Index of the study area.

CONCLUSION

This study demonstrates that seismic site response in Lempuing Subdistrict is governed by a coherent relationship among four MASW-derived seismic parameters: shear-wave velocity (V_{s30}), dominant frequency (f_0), amplification factor (A_g), and seismic vulnerability index (K_g). Rather than representing independent indicators, these parameters consistently describe the same shallow subsurface condition, characterized by moderately compact, heterogeneous alluvial deposits with limited amplification potential. The measured V_{s30} values (287.52–573.23 m/s), dominant frequencies (2.3–4.7 Hz), amplification factors (1.03–1.87), and seismic vulnerability indices (0.2–1.4) collectively indicate that most of Lempuing Subdistrict exhibits medium-to-hard site conditions and low-to-moderate seismic vulnerability, although localized variations associated with interbedded clay–sand deposits remain evident.

The principal contribution of this study is the development of the first integrated seismic microzonation for Lempuing Subdistrict based entirely on a single active-source MASW dataset. Unlike previous investigations in Bengkulu, which relied predominantly on indirect microtremor (HVSr) measurements or addressed individual geotechnical aspects separately, this study derives V_{s30} , f_0 , A_g , and K_g from one internally consistent shear-wave velocity model. The strong spatial agreement among these physically related parameters provides additional confidence in the interpreted seismic site conditions and demonstrates the capability of MASW to support integrated seismic microzonation at the subdistrict scale.

From an engineering perspective, the resulting V_{s30} map provides a practical basis for site classification in accordance with SNI 1726:2019, while the combined interpretation of A_g and K_g

identifies areas where site-specific response analysis should be considered in addition to standard code-based design procedures. Although the overall seismic vulnerability is relatively low compared with several previously reported locations in the Bengkulu region, the tectonic setting of western Sumatra and the observed lateral variability of shallow sediments indicate that earthquake hazard cannot be regarded as negligible, emphasizing the need for spatially differentiated mitigation strategies.

Future work should focus on improving subsurface characterization through joint interpretation of MASW with complementary datasets, such as HVSr measurements or borehole information, and on extending the present one-dimensional analysis to two-dimensional or three-dimensional imaging in areas exhibiting greater lateral heterogeneity. Applying the integrated MASW-based workflow developed in this study to other liquefaction-prone coastal environments will further evaluate its robustness and contribute to more reliable seismic microzonation for earthquake-resilient land-use planning and infrastructure development.

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