

IDENTIFICATION OF LIQUEFACTION POTENTIAL USING THE HVSR METHOD IN NAGARI SANIANGBAKA, X KOTO SINGKARAK DISTRICT, SOLOK REGENCY

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ABSTRACT

This study evaluates the liquefaction potential in Nagari Saniangbaka, Solok Regency, situated within the active Sumani Segment of the Great Sumatran Fault. High seismic risk arises from dominant young alluvial deposits and water-saturated conditions near Lake Singkarak. Microtremor measurements were conducted at 19 points using the Horizontal-to-Vertical Spectral Ratio (HVSR) method to determine dynamic soil parameters. The analysis yielded a natural frequency (f_0) of 0.2–14.9 Hz, amplification factor (A_0) of 0.96–9.15, seismic vulnerability index (K_g) of 0.19–96.36, and shear wave velocity (V_s) of 156.36–361.56 m/s. Critical liquefaction zones, characterized by low f_0 , high A_0 , low V_s , and high K_g , were identified at point T06 (a densely populated area) and points T11, T12, and T19 (non-residential areas). These results demonstrate that integrating these microtremor parameters effectively maps liquefaction susceptibility. These findings provide a vital technical basis for disaster mitigation and regional land-use planning in lakeside environments along active fault systems.

Keywords : *Liquefaction potential, HVSR method, Sumani Segment, Seismic vulnerability index (K_g), Nagari Saniangbaka.*



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I. INTRODUCTION

West Sumatra is recognized as one of the regions in Indonesia with the highest seismic hazard levels. This vulnerability is driven by three primary seismic sources: the subduction zone between the Indo-Australian and Eurasian plates, the Mentawai Fault System (MFS), and the Sumatran Fault System (SFS) [1]. The region's seismicity record documents a series of destructive events, including the Solok earthquake (2007), Padang earthquake (2009), Mentawai earthquake (2010), and the Painan earthquake (2016). Among these, the 2009 Padang earthquake (7.9 SR) serves as a profound example of tectonic-induced soil failure, resulting in manifestations such as soil settlement, sand boils, lateral spreading, and a significant loss of bearing strength [2].

These soil failures are direct manifestations of liquefaction a process where soil loses its shear strength due to an increase in pore water pressure induced by cyclic earthquake loading [3]. This phenomenon typically occurs in saturated, low-density granular sediment layers, where seismic vibrations cause the soil to transition from a solid to a liquid phase, thereby eliminating effective stress [4][5]. The catastrophic liquefaction event in Palu in 2018 remains a critical reminder of the potential for massive economic loss and casualties if regional vulnerability is not identified early [6].

Nagari Saniangbaka in X Koto Singkarak, Solok Regency, is geologically highly vulnerable as it is traversed by the Sumani Segment, an active part of the Sumatran Fault with high seismic potential [7]. Tectonic activity in this segment contributes to Peak Ground Acceleration (PGA) values exceeding 0.34 g in the Saniangbaka area [8]. Beyond tectonic threats, the unique topography with a dense population (approximately 156 people/km²) concentrated along the coast of Lake Singkarak exacerbates the liquefaction risk. Studies in similar environments, such as Lake Sapanca in Turkey [9] and Lake Toba in Indonesia [10], demonstrate that lakeside sediments with shallow groundwater tables are highly susceptible to liquefaction.

Despite the evident risks, a specific subsurface geophysical study identifying liquefaction potential in Nagari Saniangbaka has not yet been conducted. To address this research gap, the Horizontal to Vertical Spectral Ratio (HVSr) method is utilized as an effective, rapid, and cost-efficient identification tool [11]. Processing microtremor data via HVSr allows for the extraction of key parameters, namely natural frequency (f_0), amplification factor (A_0), and seismic vulnerability index (K_g), which characterize the local geology [12]. The effectiveness of this method has been proven in identifying liquefaction zones in various regions, including the Kathmandu Valley and Trimurti Village in Bantul [11][4].

Based on the aforementioned background, this study aims to identify the liquefaction potential in Nagari Saniangbaka using the HVSr method. The results are expected to provide accurate seismic characteristics and vulnerability mapping, serving as a scientific foundation for spatial planning and sustainable disaster mitigation strategies in the Solok Regency.

II. METHOD

Nagari Saniangbaka is geologically dominated by young alluvial deposits (Qal), which are water-saturated and unconsolidated, leading to unstable soil responses under dynamic loading. This potential is exacerbated by the concentration of residential settlements along the shores of Lake Singkarak and the location's proximity to the active Sumani Segment of the Great Sumatran Fault. The high potential for Peak Ground Acceleration (PGA) from this fault activity serves as the primary trigger for sediment destabilization, underscoring the urgency of identifying liquefaction potential in this region.

Based on these geological and tectonic conditions, microtremor data were acquired at 19 measurement points with an interval of approximately 500 m. The selection of these points accounts for variations in population density along the lakeside to obtain a representative and accurate seismic profile for disaster mitigation efforts. The spatial geological framework and the distribution of research points are presented in Figure 1 and Figure 2, respectively.

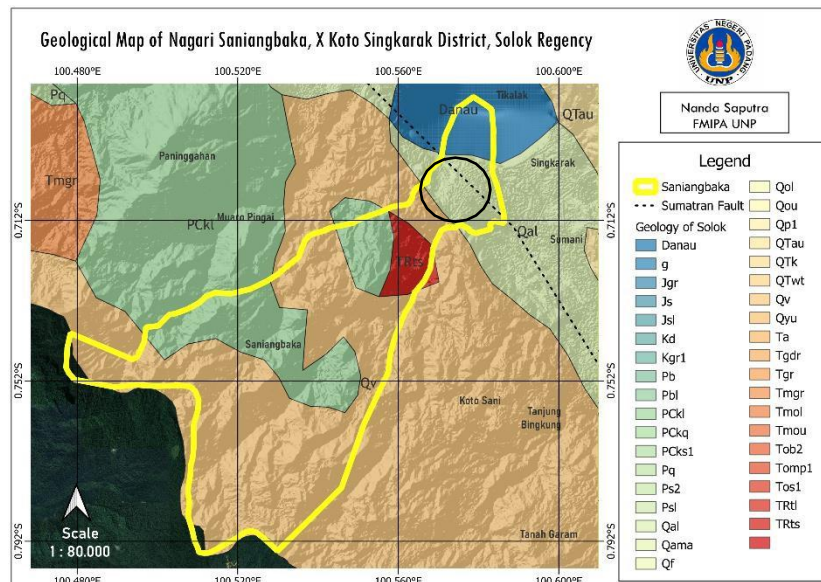


Fig. 1. Geological Map of Saniangbaka (Modified from [13])

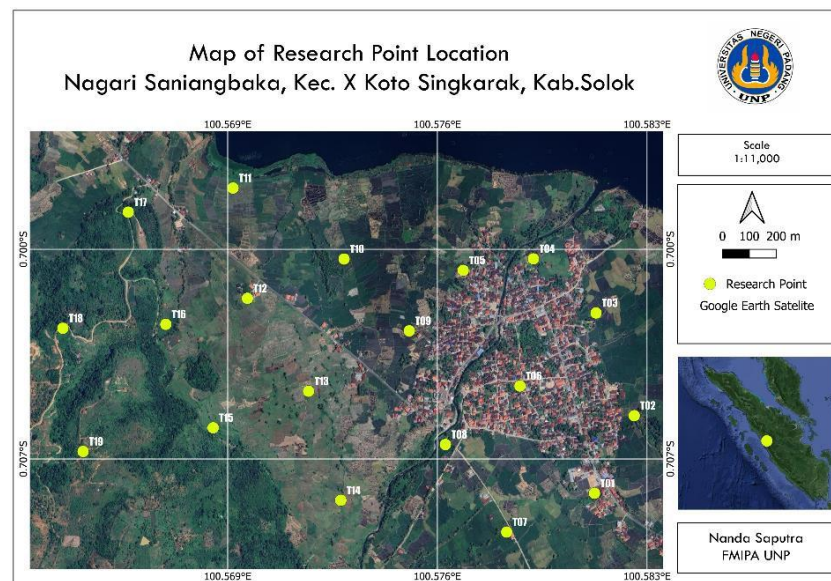


Fig. 2. Location map of the research point

Microtremor data acquisition was conducted using an S3S-type seismometer coupled with a SysmaTrack-MAE acquisition system, supplemented by GPS, a compass, and a laptop for data recording and logging. At each measurement point, microtremor signals were recorded for 20–40 minutes, depending on the ambient environmental conditions and the level of noise interference surrounding the site.

Microtremor data were processed using Easy HVSR software based on the Horizontal-to-Vertical Spectral Ratio (HVSR) method. The initial processing stages involved filtering the raw signals to remove transient noise (spikes) caused by human activity and vehicular traffic through manual selection. Subsequently, a windowing process was conducted with a 20-second duration, automatically selected from the most stable segments of the recording. To reduce spectral fluctuations, the Konno & Ohmachi smoothing method was applied with a 10% smoothing level and a bandwidth coefficient of 40 to obtain a smooth and representative H/V curve.

H/V spectral analysis was conducted within a frequency range of 0.10–15 Hz with an interval of 0.10 Hz. The horizontal spectrum was calculated as the arithmetic average of the two horizontal components and compared against the vertical spectrum. The determination of the natural frequency (f_0) and amplification factor (A_0) followed the SESAME criteria [14], which require clear and stable spectral peaks to ensure that the obtained response reflects subsurface geological conditions rather than environmental noise.

The data processing yielded the natural frequency (f_0), amplification factor (A_0), and shear wave velocity (V_s) parameters for each measurement point. Additionally, the seismic vulnerability index (K_g), which is a function of f_0 and V_s , was calculated. These parameters were subsequently classified to identify the dynamic soil characteristics and the seismic vulnerability levels of the study area. Zones characterized by low f_0 (< 2.5 Hz), $V_s < 175$ m/s, and a high seismic vulnerability index ($K_g > 10$) are indicated to have high liquefaction potential [15].

Table 1. f_0 Value Classification

Soil Classification Type	Soil Class	Natural Frequency (f_0) (Hz)	Kanai Classification	Description
IV	I	6,667 - 20	Harder surface rock. Consists of hard sandstone, gravel, etc.	Very thin surface sediment thickness, dominated by hard rock.
III	II	4 - 10	Alluvial rocks, dominated by soft sedimentary materials such as sandy-gravel, sandy hard clay, loam, etc.	Surface sediment thickness falls into the medium category, approximately 5–10 meters.
II	III	2,5 - 4	Alluvial rocks, dominated by softer sedimentary materials such as sandy-gravel, sandy hard clay, loam, etc.	Surface sediment thickness categorized as thick, approximately 10–30 meters.
I	IV	$< 2,5$	Alluvial rocks composed of deltaic sediments, topsoil, humus, etc., with a thickness exceeding 30 meters.	Very thick surface sediment layer.

(Source: Ref [16])

Table 2. A_0 Value Classification

Zone	Classification	Value
1	Low	$A < 3$
2	Medium	$3 \leq A < 6$
3	High	$6 \leq A < 9$
4	Very High	$A \geq 9$

(Source: Ref [12])

Tabel 3. V_s Value Classification

Classification Site	Shear Wave Velocity V_s (m/s)
Hard Rock	$V_s \geq 1500$
Rocks	$750 < V_s \leq 1500$
Soft Rock	$350 < V_s \leq 750$
Medium Soil	$175 < V_s \leq 350$
Soft Soil	$V_s < 175$

(Source: Ref [17])

The natural frequency (f_0) and amplification factor (A_0) values derived from the HVSR curve analysis are utilized to calculate the seismic vulnerability index (K_g), which represents the susceptibility of the ground to vibrations, particularly those induced by seismic activity. The calculation is performed using the equation formulated by Nakamura [18].

$$K_g = \frac{A_0^2}{f_0} \quad (1)$$

Subsequently, the seismic vulnerability index (K_g) values obtained at the measurement points were classified.

Table 4. K_g Value Classification

Zone	Classification	Value
1	Low	$K_g < 3$
2	Medium	$3 < K_g < 6$
3	High	$K_g > 6$

(Source: Ref [19])

The results of the four parameters (f_0 , A_0 , V_s dan K_g) were subsequently visualized as spatial distribution maps through an interpolation process using QGIS software. These distribution maps are utilized to identify liquefaction potential within the study area.

III. RESULTS AND DISCUSSION

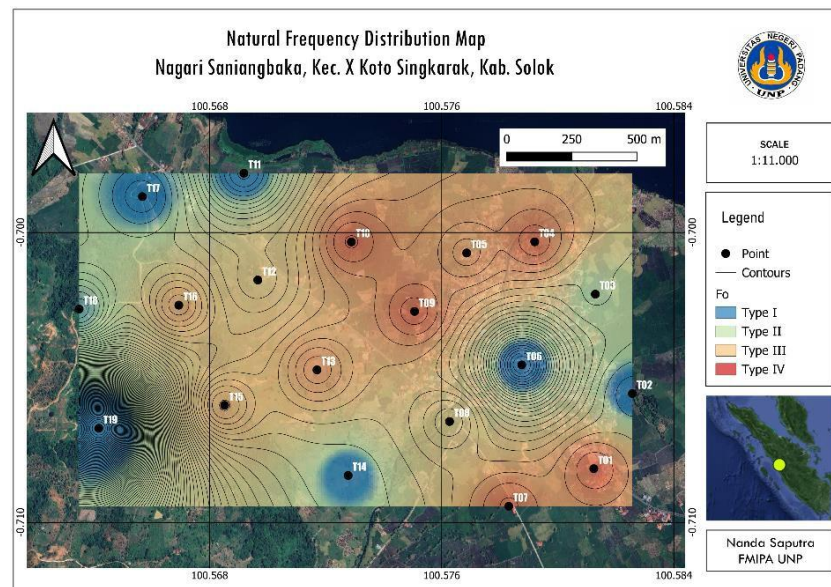
A. Natural Frequency (f_0)

Natural frequency is (f_0) a parameter that represents the vibration characteristics of rock layers in a region based on their physical properties [20]. This value has an inverse relationship with the thickness of the sediment layer; a low natural frequency indicates a thicker sediment layer, and vice-versa [21]. Based on the HVSR analysis conducted in Nagari Saniangbaka, the f_0 values range from 0.2 Hz to 14.9 Hz. This finding is consistent with research in similar geological environments, such as Blitar, which reported a range of 1.70 Hz – 10.39 Hz [22], and Bantul, with a range of 1.60 Hz – 9.94 Hz in alluvial sediments [4]. Such consistency indicates that the values in the study area fall within a scientifically reasonable range and accurately reflect the regional geological conditions. The detailed natural frequency values for each measurement point are presented in Table 5.

Table 5. f_0 Values at Measurement Points

Research Point	Natural	Soil Classification	
	Frequency (f_0) (Hz)	Type	Class
T08, T12, T15, T16, T05, T13, T01, T04, T07, T09, T10 T18, T03	8.3 - 14.9	IV	I
T06, T19, T14, T02, T11, T17	3.2 - 3.9	II	III
	0.2 - 1.5	I	IV

The spatial distribution of natural frequency (f_0) values in Nagari Saniangbaka is presented in Figure 3, which illustrates the variations in soil types based on the microtremor data processing results.

**Fig. 3.** Spatial Distribution Map of Natural Frequency (f_0) in Nagari Saniangbaka.

The natural frequency (f_0) distribution map in Nagari Saniangbaka is categorized into four types based on geological characteristics. Zones with low f_0 values (Type I: 0.2–1.5 Hz) were identified at points T02, T06, T11, T14, T17, and T19. These areas are indicated in blue, concentrated in the central and southwestern parts of the study area, which suggests the presence of soft sediment layers with significant thickness. Meanwhile, Type II (3.2–3.9 Hz) was observed at points T18 and T03, marked in green, reflecting a moderate surface sediment thickness occurring locally in the northwest and southeast. Conversely, zones with high f_0 values (Type IV: 8.3–14.9 Hz) dominate the eastern and northeastern sectors of the study area, encompassing points T01, T04, T05, T07, T08, T09, T10, T12, T13, T15, and T16. This region, shown with a red-to-orange color gradient, reflects relatively stiff soil conditions with the presence of shallow bedrock. Seismically, areas with Type IV characteristics are considered more stable compared to regions with low natural frequencies. It should be noted that the Type III classification was not encountered across the study sites.

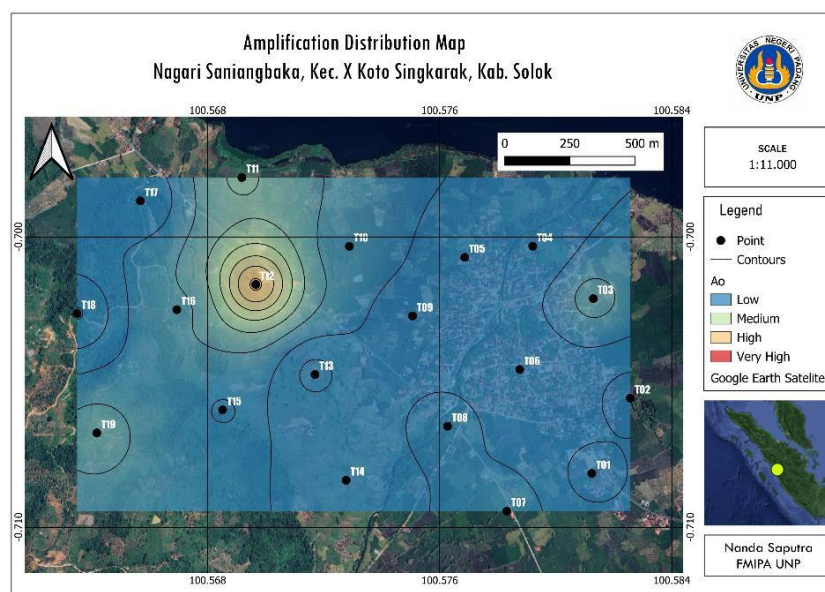
B. Amplification (A_0)

Amplification is a phenomenon where seismic waves are magnified as they propagate from a stiff medium to a softer medium. Physically, this is triggered by a significant impedance contrast between rock layers; the greater the difference in characteristics between the media, the higher the resulting wave amplification [16]. Furthermore, the amplification factor (A_0) can increase if the soil or rock layers have undergone deformation such as weathering, folding, or faulting which significantly alters their physical properties [23]. The results of the H/V curve analysis in Nagari Saniangbaka show that the amplification values range from 0.96 to 9.15. Detailed amplification values for each measurement point are presented in Table 6.

Table 6. A_0 Values at Measurement Points

Research Point	A_0 Value	Classification
T18, T02, T01, T13, T04, T17, T06, T09, T05, T14, T15	0.96 – 2.96	Low
T08, T07, T10, T16, T03, T19, T11	3.25 – 5.13	Medium
T12	9.15	Very High

The spatial distribution of the amplification factor (A_0) in Nagari Saniangbaka is presented in Figure 4, which illustrates the variations in ground amplification levels based on the microtremor data processing results.

**Fig. 4.** Spatial Distribution Map of the Amplification Factor (A_0) in Nagari Saniangbaka.

Based on the spatial distribution map in Figure 4, the amplification factor (A_0) in Nagari Saniangbaka is classified into four levels: low, moderate, high, and very high. The majority of the study area is dominated by low amplification levels (0.96 – 2.96), which include points T01, T02, T04, T05, T06, T09, T13, T14, T15, T17, and T18, with distributions in the western, southeastern, and northern parts. Furthermore, moderate amplification levels (3.25 – 5.13) were identified at points T03, T07, T08, T10, T11, T16, and T19, distributed from the central to the eastern parts of the measurement area. This zone represents a transition area toward ground conditions that are more susceptible to seismic wave amplification. Although the high amplification class was not widely encountered, an anomaly was observed at point T12 with a very high amplification value of 9.15. The range of A_0 values in this study remains consistent with research in similar geological environments, such as in Bantul with a range of 2.35 – 4.43 [4] and in Mamuju, West Sulawesi, with a range of 1.5 – 11 [15]. Thus, the high value at point T12 is not a data outlier, but rather a manifestation of a distinct local subsurface structure compared to the other observation points.

C. Seismic Vulnerability Index (K_g)

The seismic vulnerability index (K_g) is a parameter that represents the susceptibility of soil layers to deformation under seismic loading. This index is widely utilized to evaluate the potential for infrastructure damage resulting from ground motion [24]. Physically, high K_g values are typically found in unconsolidated soft sediment layers, indicating that such areas possess a high risk regarding earthquake shaking. Conversely, low K_g values reflect stiff and stable rock layers, where the perceived vibration energy tends to be lower [12]. Based on the H/V curve analysis in Nagari Saniangbaka, the obtained K_g values range from 0.19 to 96.36. This range is consistent with HVSr studies in similar geological environments, such as in Ambon (0.57–58.97) [25] and Mamuju, West Sulawesi (0.2–127.8) [15]. Such data consistency suggests that the variations at the study site reflect heterogeneous subsurface conditions while remaining within scientifically reasonable limits. Detailed seismic vulnerability index values for each measurement point are presented in Table 7.

Table 7. Kg Values at Measurement Points

Research Point	Kg Value	Classification
T01, T13, T18, T04, T09, T05, T15, T07, T10, T08, T16, T02 T17, T03	0.19 - 2.42	Low
T14, T12, T11, T06, T19	3.29 - 4.87	Medium
	6.40 - 96.36	High

The spatial distribution of the seismic vulnerability index (Kg) in Nagari Saniangbaka is presented in Figure 5, which illustrates the variation in vulnerability levels based on the results of microtremor data processing.

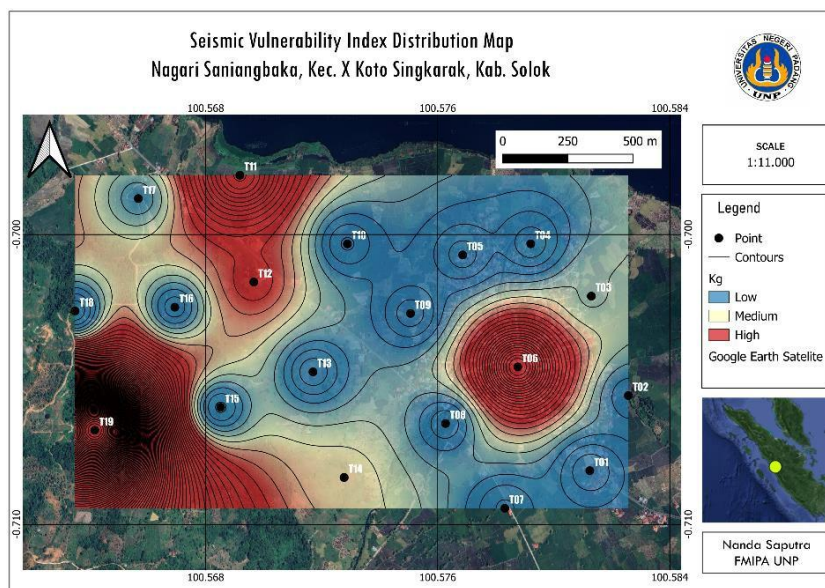


Fig. 5. Spatial Distribution Map of the Seismic Vulnerability Index (Kg) in Nagari Saniangbaka.

Based on the spatial distribution map in Figure 5, the seismic vulnerability index (Kg) in Nagari Saniangbaka is classified into three levels: low, moderate, and high. The low vulnerability category, with a range of 0.19–2.42, dominates the majority of the study area, encompassing points T01, T02, T04, T05, T07, T08, T09, T10, T13, T15, T16, and T18. This area is indicated in blue and is widely distributed across the northeastern and southeastern parts of the map. Meanwhile, the moderate vulnerability category (3.29–4.87) was identified locally at point T17 in the northwestern part and point T03 in the northeastern part, marked with a greenish color. The high vulnerability zone is characterized by a deep red color gradient, covering the areas around points T06, T11, T12, T14, and T19, with a range of 6.40–96.36. The highest value was recorded at point T19 at 96.36, indicating a very significant potential for ground deformation hazard and seismic vulnerability in the region.

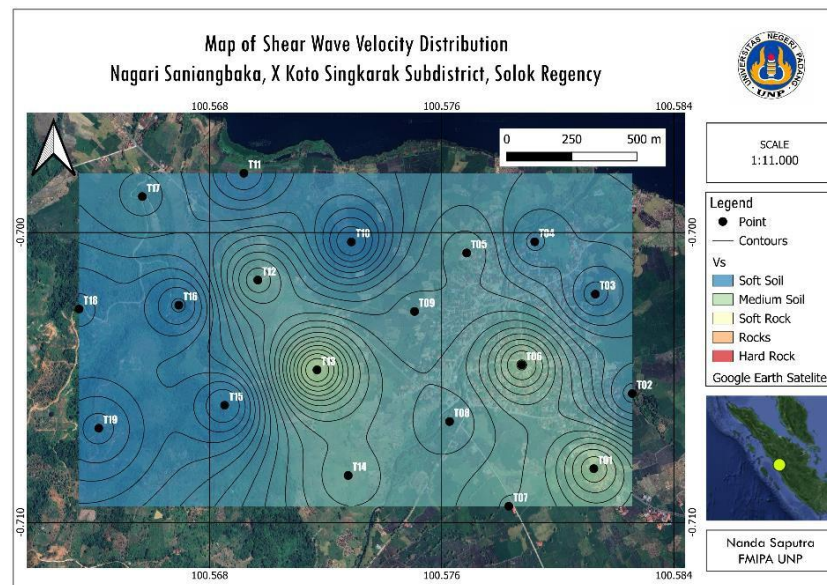
D. Shear Wave Velocity (Vs)

Shear wave velocity (Vs) is the propagation speed of secondary waves through an elastic medium and serves as a primary parameter in determining soil stiffness [26]. Physically, soft materials exhibit lower Vs values compared to hard rocks because shear wave velocity is directly proportional to the density and stiffness of the rock [27]. Based on the HVSR curve analysis conducted in Nagari Saniangbaka, the Vs values range from 156.36 m/s to 361.56 m/s. This range aligns with research in similar geological environments, such as the HVSR study in Mamuju, West Sulawesi, which reported Vs values of 108–238 m/s [15]. These findings are consistent with the characteristics of Quaternary alluvial sediments, which are generally unconsolidated. In modern liquefaction potential analysis, Vs is a crucial parameter as it directly correlates with soil shear strength at small strains [28]. Detailed shear wave velocity values for each measurement point are presented in Table 8.

Table 8. Vs Values at Measurement Points

Research Point	Vs Value (m/s)	Classification
T19, T16, T15, T10, T11 T18, T03, T04, T02, T17, T08, T09, T05, T12, T14, T07, T06, T01	156.36 - 173.11	Soft Soil
T13	361.56	Soft Rock

The spatial distribution of shear wave velocity (V_s) values in Nagari Saniangbaka is presented in Figure 6, which illustrates the variations in soil stiffness based on the microtremor data processing results.

**Fig. 6.** Spatial Distribution Map of Shear Wave Velocity (V_s) in Nagari Saniangbaka.

The spatial distribution map of shear wave velocity (V_s) in Figure 5 is classified based on the stiffness levels of the subsurface materials. The results of the microtremor analysis in Nagari Saniangbaka indicate a range of values between 156.36 m/s and 361.56 m/s. Based on site classification standards, the study area is divided into three primary categories: soft soil, medium soil, and soft rock. The soft soil category (156.36–173.11 m/s) was identified at points T10, T11, T15, T16, and T19, which are spatially concentrated in the northwestern part of the study area. This zone is dominated by loose sediment materials with low density that tend to amplify shaking during an earthquake. Meanwhile, the majority of the study area is classified as medium soil (177.77–336.7 m/s), encompassing points T01, T02, T03, T04, T05, T06, T07, T08, T09, T12, T14, T17, and T18. The materials in this zone possess denser and stiffer characteristics, resulting in moderate amplification levels of seismic waves. The soft rock category was only found locally at point T13 with a value of 361.56 m/s, located in the central to southern region. This location indicates the presence of compact and dense subsurface materials with relatively low wave amplification potential.

E. Integrated Analysis of Microtremor Parameters for Liquefaction Potential

The high liquefaction potential in Nagari Saniangbaka is driven by a complex interaction between geological, hydrological, and dynamic soil parameters. Geologically, the region is dominated by Quaternary alluvium (Qal) deposits consisting of soft and poorly consolidated sediments. These unconsolidated material characteristics pose a significant risk of deformation when subjected to dynamic loading from the active Sumani Segment [29]. This condition is further exacerbated by its geographical location on the shores of Lake Singkarak, where a shallow water table creates high water saturation within the sediment pore layers. This phenomenon is consistent with cases observed at Lake Sapanca [9] and Lake Toba [10], confirming that proximity to water bodies and sediment saturation are key factors in increasing liquefaction sensitivity.

Analytical analysis of microtremor parameters reinforces these indications. Data integration reveals that zones with critical vulnerability exhibit a consistent pattern: low natural frequency ($f_0 < 2.5$ Hz) reflecting thick sediments, combined with low shear wave velocity ($V_s < 175$ m/s) as an indicator of soft soil, and a high seismic

vulnerability index ($K_g > 10$) [15]. Extreme values represent the magnitude of deformation that soil layers may undergo during seismic shaking. The validity of this relationship is supported by the findings of Huang & Tseng [30] and Hermawan et al. [4], which state that high and low values serve as strong empirical indicators for field liquefaction events. Based on the synthesis of these physical parameters and local geological conditions, point T06 located in a densely populated area along with points T11, T12, and T19, are identified as zones with the highest liquefaction risk, requiring priority in disaster mitigation strategies.

IV. CONCLUSION

Based on the microtremor analysis using the Horizontal-to-Vertical Spectral Ratio (HVSr) method in Nagari Saniangbaka, it can be concluded that the dynamic soil characteristics in the study area exhibit a natural frequency (f_0) range of 0.2 – 14.9 Hz, an amplification factor (A_0) of 0.96 – 9.15, a seismic vulnerability index (K_g) of 0.19 – 96.36, and a shear wave velocity (V_s) of 156.36 – 361.56 m/s. The integration of these parameters identifies high liquefaction potential at point T06, which is a densely populated residential area, as well as points T11, T12, and T19 in sparsely populated zones. The high vulnerability values associated with low frequency and velocity values at these locations indicate the presence of soft sediment layers that are highly susceptible to deformation and structural soil failure due to seismic shaking from the Sumani Segment. The results of this study provide an important contribution as a scientific reference in formulating targeted disaster mitigation strategies for the community along the shores of Lake Singkarak. Furthermore, this vulnerability mapping can serve as a technical foundation for local governments in spatial planning and infrastructure development evaluation to minimize the risk of material loss and casualties in the future.

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