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Characterization of Groundwater Conditions Using HVSR-Derived Vp/Vs Ratio and Poisson's Ratio in Muara Bangkahulu District

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ABSTRACT

Muara Bangkahulu District, Bengkulu City, is predominantly underlain by unconsolidated sediments that influence groundwater occurrence and subsurface hydrogeological conditions. This study aims to characterize groundwater-related subsurface conditions using the Vp/Vs ratio and Poisson's ratio derived from Horizontal-to-Vertical Spectral Ratio (HVSR) microtremor inversion and to evaluate their relationship with groundwater table observations. Microtremor measurements were conducted at 34 observation points and complemented by groundwater table measurements from nearby wells. The data were processed using Geopsy, HV-Inv, and Surfer to generate two-dimensional subsurface models and spatial distribution maps. The inversion results yielded Vp/Vs ratios ranging from 0.8 to 3.6 and Poisson's ratios from 0.10 to 0.64. Values of Vp/Vs > 1.73 and Poisson's ratio > 0.25 were interpreted as indicative of water-saturated unconsolidated sediments. The highest values were observed in Kandang Limun and Pematang Gubernur, where MB5 recorded a Vp/Vs ratio of 3.12 and Poisson's ratio of 0.36, while MB16 recorded 3.51 and 0.40, respectively. These results are qualitatively consistent with shallow groundwater indicated by nearby well observations. The integration of HVSR-derived elastic parameters and groundwater observations provides a site-specific assessment of groundwater-related subsurface conditions in the study area.

I. INTRODUCTION

The groundwater table, which marks the boundary between the unsaturated and saturated zones, is an important hydrogeological parameter for evaluating aquifer conditions and groundwater availability (Baird & Low, 2022). In coastal areas, groundwater systems are particularly vulnerable to seawater intrusion and groundwater level fluctuations, making groundwater table characterization essential. Muara Bangkahulu District, a coastal area of Bengkulu City, is dominated by unconsolidated sediments that strongly influence groundwater occurrence. The proximity to the coastline increases the vulnerability of shallow aquifers to seawater intrusion and groundwater level changes. Therefore, a reliable and non-invasive method is needed to investigate groundwater conditions. The Horizontal-to-Vertical Spectral Ratio (HVSR) method, combined with inversion analysis, can estimate elastic parameters such as Vs, Vp, and Poisson's ratio, which are related to lithology, porosity, and water saturation.

Besides influencing groundwater availability, subsurface conditions in coastal areas also affect the region's response to geological hazards. Variations in groundwater table depth, controlled by geological conditions, rainfall, and groundwater extraction (Fan et al., 2021), modify the degree of soil saturation and consequently influence the mechanical properties of near-surface sediments. In earthquake-prone regions, these changes may affect ground response and the susceptibility of unconsolidated deposits to seismic hazards. Therefore, mapping groundwater-related subsurface characteristics is important for both groundwater resource assessment and seismic hazard evaluation (Taylor et al., 2020). Groundwater table depth is commonly measured using dug wells or boreholes; however, these methods are limited to discrete locations and can be time-consuming. As an alternative, geophysical methods such as the Horizontal-to-Vertical Spectral Ratio (HVSR) provide a non-invasive approach for investigating subsurface conditions. The elastic properties of subsurface materials, which are influenced by lithology, porosity, and water saturation, can be estimated through HVSR inversion and used to characterize aquifers and groundwater table depth.

The Horizontal-to-Vertical Spectral Ratio (HVSR) method has been widely applied to characterize subsurface structures using ambient seismic noise. The theoretical basis and practical implementation of the HVSR technique have been extensively established through the SESAME Project (Bard et al., 2004), subsequent investigations of ambient vibration wavefields (Bonnefoy-Claudet et al., 2006), and later methodological developments for site characterization and subsurface interpretation (Albarello & Lunedei, 2013). Previous studies have also demonstrated that HVSR can support groundwater and aquifer investigations by estimating sediment thickness, bedrock geometry, and elastic properties related to groundwater occurrence (Picozzi et al., 2021). More recently, HVSR-derived parameters have also been applied to evaluate aquifer potential in unconsolidated coastal sediments through the interpretation of Vs and Poisson's ratio (Nurwidyanto et al., 2026).

However, the present study differs from previous investigations in its emphasis on the Vp/Vs ratio and Poisson’s ratio derived from HVSR inversion and their qualitative comparison with groundwater table observations in a tropical coastal environment. While previous studies have demonstrated the usefulness of HVSR-derived parameters for groundwater-related subsurface characterization, the present study further integrates Vp/Vs, Poisson’s ratio, geological information, and groundwater table observations from nearby wells to provide additional qualitative support for groundwater-related interpretations. This approach is particularly relevant to Muara Bangkahulu District, where unconsolidated alluvial and swamp deposits dominate the shallow subsurface and coastal conditions may influence groundwater availability. Therefore, the contribution of this study is to provide a site-specific qualitative assessment of groundwater-related subsurface conditions based on the integration of HVSR-derived elastic parameters and independent groundwater observations.

II. METHOD

Microtremor measurements were conducted at 34 observation points distributed throughout Muara Bangkahulu District to represent the spatial variability of subsurface conditions. The number of observation points was selected to provide adequate spatial coverage across the study area while considering field accessibility, relatively low levels of transient cultural noise, and the availability of nearby residents' wells for groundwater table observations. The 34 observation points were distributed across the study area to capture lateral variations in subsurface conditions and were paired with 34 representative dug wells located near the corresponding HVSR observation points. At each well, the total well depth and groundwater table depth were measured and recorded. These measurements were subsequently compared qualitatively with the corresponding Vp/Vs ratio and Poisson's ratio values obtained from HVSR inversion to assess their consistency in identifying groundwater-related subsurface conditions. The distribution of the observation points and wells is presented in Figure 1.

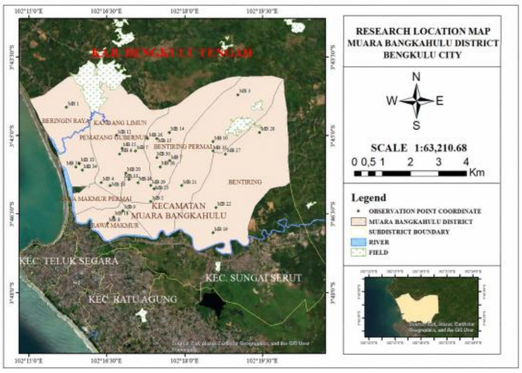


Figure 1 Map of the study area overlaid with the locations of the observation points.

Ambient vibration data were recorded using a PASI Mod Gemini 2 short-period seismograph equipped with a three-component sensor. At each observation point, ambient vibration was recorded for 30–45 minutes using a sampling frequency of 100 Hz. The sensor was installed on level ground with the horizontal components oriented approximately toward the north–south and east–west directions to ensure consistency among measurements. The distance between adjacent observation points was adjusted according to field accessibility and geological conditions, generally ranging from several hundred metres to approximately one km. To facilitate two-dimensional (2D) subsurface interpretation, three representative survey lines were established based on the spatial distribution of the observation points.

Survey Lines 1 and 2 were oriented in the northwest–southeast (NW–SE) direction to represent the dominant geological trend of the study area, whereas Survey Line 3 was oriented in the southwest–northeast (SW–NE) direction to provide a cross-sectional view perpendicular to the main geological trend. Survey Line 1 consists of observation points MB31, MB34, MB4, MB32, MB2, and MB19. Survey Line 2 consists of observation points MB20, MB13, MB16, MB29, MB25, and MB22. Survey Line 3 consists of observation points MB6, MB11, MB5, MB24, MB15, and MB14. These survey lines were used to generate two-dimensional inversion models of the Vp/Vs ratio and Poisson's ratio, allowing the lateral variation of subsurface properties to be interpreted across the study area. The inverted Vp/Vs ratio and Poisson's ratio were interpreted to classify subsurface materials according to their elastic properties and groundwater saturation. In general, compact rocks are characterized by relatively low Vp/Vs and Poisson's ratio values, whereas unconsolidated water-saturated sediments exhibit higher values. The interpretation adopted in this study follows Hersir and Bjornsson (1991), Ahmed et al. (2024), Wang et al. (2024), and Bashir et al. (2024), which relate elastic parameters to lithology, porosity, and saturation conditions.

The acquired microtremor data were processed using Geopsy based on the Horizontal-to-Vertical Spectral Ratio (HVSR) method. The recordings were divided into 20 s windows, and transient noise was removed using the anti-trigger function. Fourier spectra were smoothed using the Konno–Ohmachi function (Konno & Ohmachi, 1998) with a smoothing coefficient of 40 over a frequency range of 0.5–20 Hz. The quality of the HVSR curves was evaluated following the SESAME (2004) guidelines, and only stable curves with clear spectral peaks were retained for inversion. The processed HVSR curves were subsequently analyzed using HV-Inv to estimate the Vp/Vs ratio and Poisson's ratio for subsurface interpretation, as illustrated in Figure 2.

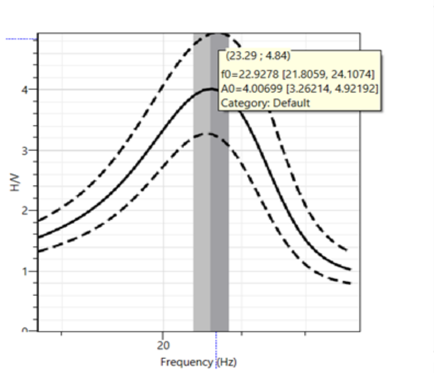


Figure 2 Example of an HVSR curve obtained from data processing at Observation Point 33.

As shown in Figure 2 (Observation Point 33), the processed HVSR curve exhibits a prominent single peak with a clear fundamental resonant frequency (*f0*) of 22.93 Hz (range: 21.81–24.11 Hz) and a corresponding peak amplitude (*A0*) of 4.01 (range: 3.26–4.92), fulfilling the SESAME (2004) criteria for curve clarity and stability. The inversion was conducted by defining a initial 4-layer earth model based on local geological bore logs. The search parameter ranges were set to Vs = 100–800 m/s, layer thickness = 1–30 m, and Poisson's ratio = 0.2–0.49. The Monte Carlo algorithm performed 20,000 iterations per curve to search for the global minimum misfit value. The Vp/Vs ratio and Poisson's ratio were specifically selected as primary indicators because primary wave velocity (Vp) increases significantly in water-saturated media while shear wave velocity (Vs) remains unaffected, causing a sharp rise in both ratios (Vp/Vs > 1.9 and Poisson's ratio > 0.4) within saturated groundwater-bearing zones.

III. RESULT AND DISCUSSION

Data hasil pengukuran konfigurasi Wenner-Schlumberger diolah menggunakan ResIPy dengan dua The HVSR inversion results reveal considerable spatial variations in the Vp/Vs ratio and Poisson's ratio across Muara Bangkahulu District. The geological setting of Muara Bangkahulu District is presented in Figure 3.

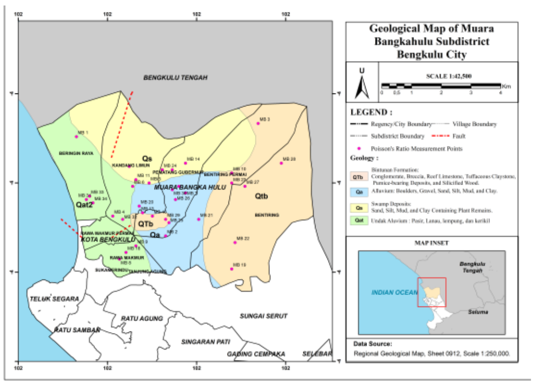
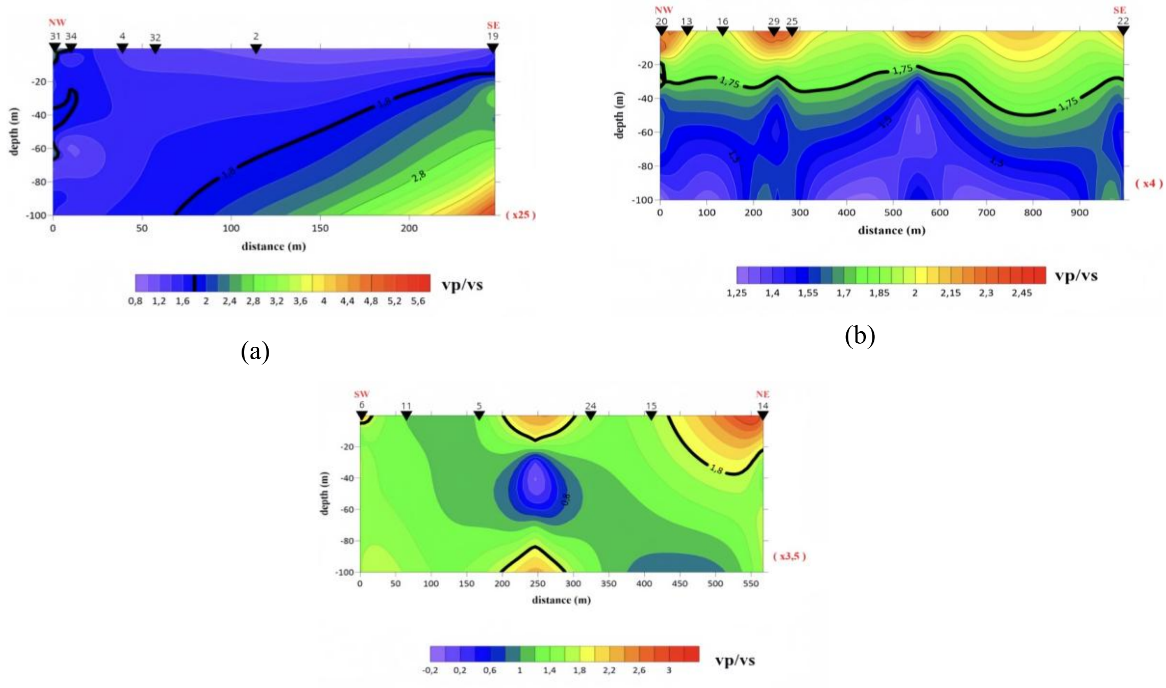


Figure 3 Geological map of Muara Bangkahulu District overlaid with the observation locations.

Figure 3 shows the geological conditions of Muara Bangkahulu District, Bengkulu City, along with the distribution of the 34 observation points. The study area is predominantly underlain by Alluvium (Qa), consisting of gravel, sand, silt, mud, and clay, and Swamp Deposits (Qs), composed of sand, silt, mud, clay, and plant remains. The area also includes Alluvial Terrace (Qat_2), consisting of sand, silt, clay, and gravel, and the Bitunan Formation (Qtb), which comprises conglomerate, breccia, reef limestone, tuffaceous claystone, sandstone, and silicified wood. The distribution of the observation points across these geological units provides a basis for relating variations in subsurface geological conditions to the derived elastic parameters. In particular, the relatively unconsolidated alluvial and swamp deposits, especially within the Qa and Qs units, are important for interpreting the Vp/Vs ratio and Poisson's ratio, as these materials may have higher porosity and water content. Thus, Figure 3 provides an important geological context for interpreting variations in the elastic parameters and identifying subsurface conditions associated with groundwater occurrence in the study area.

In general, Poisson's ratio values greater than 0.25 and *Vp/Vs* ratios greater than 1.73 are considered indicative of groundwater aquifers (Hersir & Bjornsson, 1991). The *Vp/Vs* ratio is an important elastic parameter for interpreting the lithological characteristics of subsurface layers. Values exceeding 1.73 generally indicate water-saturated materials, assuming that pore spaces are filled with fluids, whereas values below 1.73 suggest relatively unsaturated materials or the possible presence of gas. The two-dimensional (2D) *Vp/Vs* models for the three survey lines are shown in Figure 4.

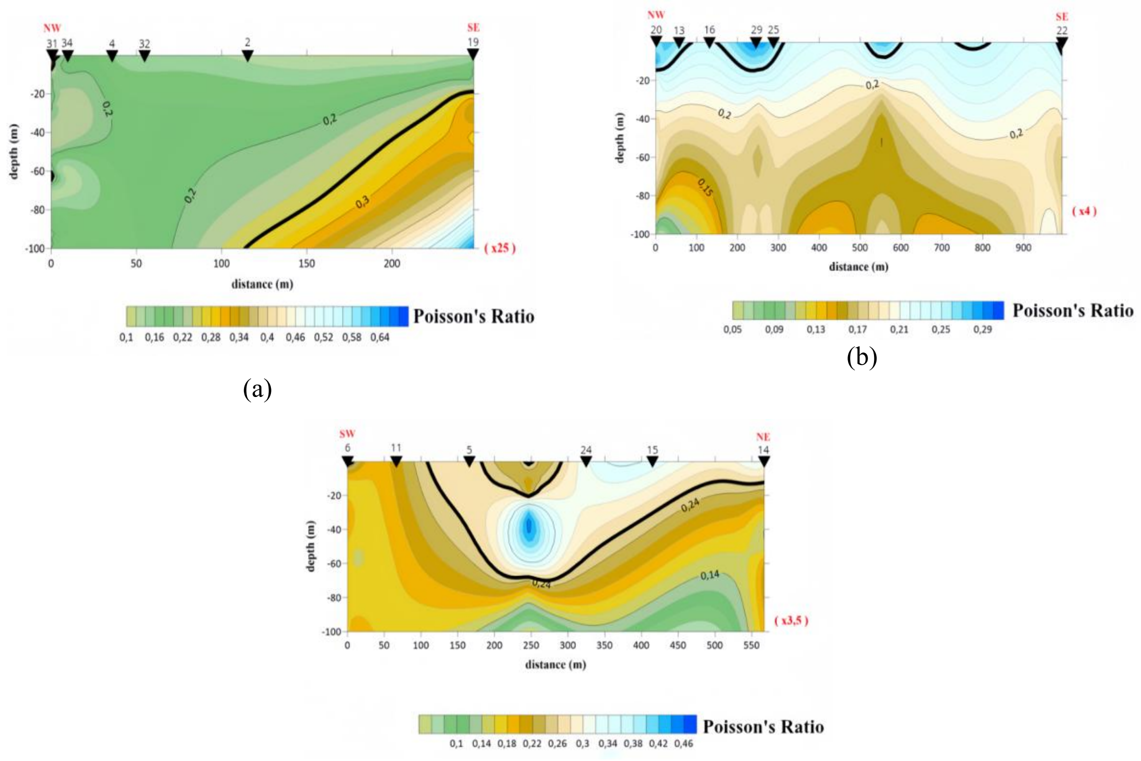


(a) (b) (c)

Figure 4 2D *Vp/Vs* models for (a) Survey Line 1, (b) Survey Line 2, and (c) Survey Line 3.

Based on the Vp/Vs models, Survey Lines 1 and 2 (NW–SE) and Survey Line 3 (SW–NE) exhibit Vp/Vs values ranging from approximately 0.8 to 3.0, with dominant values between 1.4 and 2.2, indicating considerable lateral and vertical variations in subsurface elastic properties. Values below 1.5 represent relatively rigid materials, values between 1.5 and 2.2 correspond to moderately consolidated to unconsolidated sediments, and values above 2.2 indicate higher porosity, greater fluid content, or lithological variations. The spatial distribution of Vp/Vs further indicates that low values (1.5–1.7) are associated with compact, relatively dry materials, intermediate values (1.8–2.0) represent transitional zones, and high values (>2.0) indicate water-saturated unconsolidated sediments. Increasing groundwater saturation raises the Vp/Vs ratio because pore water increases compressional-wave velocity (Vp), while shear-wave velocity (Vs) changes only slightly.

Consequently, higher Vp/Vs and Poisson's ratio values indicate greater saturation and reduced sediment stiffness, supporting the interpretation of shallow groundwater-bearing unconsolidated deposits. Poisson's ratio is also used to characterize material compaction, porosity, and groundwater saturation. Values greater than 0.25 generally indicate water-saturated sediments, whereas values below 0.25 correspond to relatively compact or unsaturated materials. Therefore, Poisson's ratio is interpreted together with the Vp/Vs ratio to improve lithological characterization. The two-dimensional Poisson's ratio models for the three survey lines are presented in Figure 5.



(a)

(b)

(c)

Figure 5 2D Poisson’s ratio models for (a) Survey Line 1, (b) Survey Line 2, and (c) Survey Line 3.

The Poisson’s ratio models show values ranging from approximately 0.10 to 0.64, with most values between 0.15 and 0.30, indicating variations in the compaction and saturation conditions of the subsurface materials. Lower values (<0.15) represent relatively stiff and less saturated materials, whereas higher values (>0.30) indicate softer, more porous, and potentially water-saturated sediments. The coincidence of high Vp/Vs and Poisson’s ratio values suggests the presence of unconsolidated deposits with higher water content.

Spatial distribution maps indicate that the highest elastic parameters occur in Kandang Limun and Pematang Gubernur Observation point MB5 (Kandang Limun) recorded a Vp/Vs ratio of 3.12 and a Poisson's ratio of 0.36, with a groundwater table depth of 10 - 60 m and a well depth of 13 m. Similarly, MB16 (Pematang Gubernur) yielded a Vp/Vs ratio of 3.51 and a Poisson's ratio of 0.40, with a groundwater table depth of 10 - 25 m and a well depth of 15 m. The relatively high Vp/Vs and Poisson's ratio values at these locations are qualitatively consistent with the presence of shallow groundwater indicated by the well observations.The integration of Vp/Vs and Poisson’s ratio provides a more reliable interpretation of lithology, porosity, and groundwater saturation than either parameter alone, demonstrating the potential of HVSR inversion for groundwater characterization in tropical coastal environments.

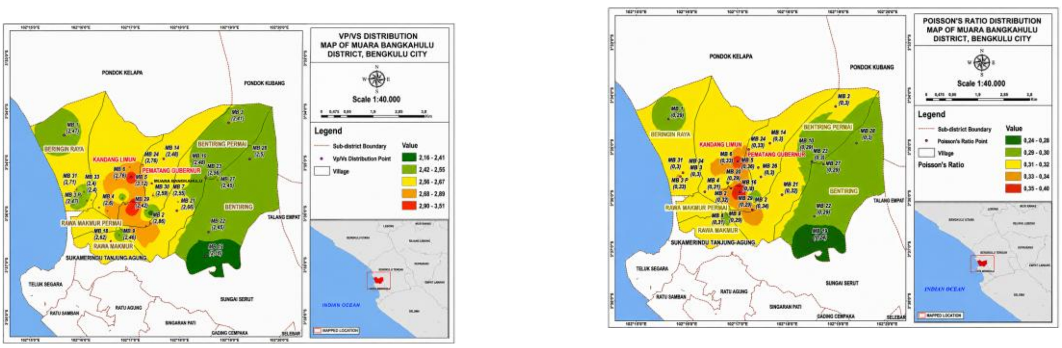


Figure 6 Spatial distribution maps+ of the Vp/Vs ratio and Poisson’s ratio.

This interpretation is generally consistent with previous HVSR-based groundwater investigations. Sorensen and Asten (2007) demonstrated that microtremor methods can provide useful information on subsurface structures related to groundwater systems, particularly by identifying variations in regolith thickness and basement geometry. More recently, Nurwidyanto et al. (2026) applied HVSR-derived Vs and Poisson's ratio to evaluate aquifer potential in unconsolidated coastal sediments and identified potential aquifer zones based on variations in these elastic parameters. The present findings are consistent with these studies in demonstrating that HVSR-derived elastic parameters can provide information related to groundwater-bearing subsurface materials.This interpretation is consistent with the regional geological setting, which is characterized by young alluvial and swamp deposits composed of sand, silt, and clay. Based on the integrated interpretation, the subsurface materials can be classified as follows:

Table 1 Classification of subsurface materials based on *Vp/Vs* ratio and Poisson's ratio adopted in this study.

Zone Classification	Vp/Vs Ratio	Poisson's Ratio	Material Characteristics	Soil/Rock Condition
Hard rock / very dense sand	< 1,60	< 0,25	Very compact, low porosity	Unsaturated
Dense sand	1,60–1,80	0,25–0,30	Compact, moderate permeability	Partially saturated
Silty sand	1,80–2,00	0,30–0,35	Moderately compact	Beginning to become saturated
Loose sandy silt	2,00–2,20	0,35–0,40	Less compact	Water-saturated
Soft clay	2,20–2,50	0,40–0,45	Soft, high porosity	Highly saturated
Young alluvial or swamp deposits	> 2,50	> 0,45	Very soft	Fully saturated

Table 1 presents the classification scheme adopted in this study. The threshold values were synthesized from previous studies relating elastic parameters to lithology, porosity, and groundwater saturation (Ahmed et al., 2024; Wang et al., 2024; Bashir et al., 2024) and were adapted to the geological characteristics of unconsolidated coastal sediments in Muara Bangkahulu District. This relationship suggests that groundwater saturation plays a significant role in controlling the mechanical properties of subsurface materials and influences their dynamic response to earthquake loading. Therefore, integrating HVSR analysis with groundwater table observations provides valuable information for identifying weak zones in seismically vulnerable areas (Galone et al., 2024).

IV. CONCLUSION

The microtremor investigation using the Horizontal-to-Vertical Spectral Ratio (HVSR) method provides a qualitative assessment of groundwater-related subsurface conditions in Muara Bangkahulu District using inversion-derived Vp/Vs ratio and Poisson's ratio. The Vp/Vs ratio ranged from approximately 0.8 to 3.6, while Poisson's ratio varied from 0.10 to 0.64. Zones with Vp/Vs > 1.73 and Poisson's ratio > 0.25 were interpreted as water-saturated unconsolidated sediments associated with shallow groundwater. The highest values occurred in the Kandang Limun and Pematang Gubernur areas, where the Vp/Vs ratio exceeded 2.5 and Poisson's ratio exceeded 0.45, indicating fully saturated young alluvial deposits with high groundwater potential. These results demonstrate that integrating HVSR-derived elastic parameters with groundwater table observations provides a practical, non-invasive approach for identifying groundwater-bearing zones in unconsolidated coastal sediments.

The study provides a qualitative assessment of groundwater-related subsurface conditions in Muara Bangkahulu District based on the integration of HVSR-derived Vp/Vs ratio, Poisson's ratio, geological information, and groundwater table observations. Areas characterized by relatively high Vp/Vs and Poisson's ratio values, particularly Kandang Limun and Pematang Gubernur, indicate greater potential for shallow groundwater and may be prioritized for further groundwater investigation and development. However, because the study area is located in a coastal environment and the present analysis does not directly evaluate salinity or seawater intrusion, groundwater development in areas close to the coastline should be accompanied by monitoring of groundwater levels and water quality. Future studies should incorporate borehole data, geotechnical investigations, and complementary geophysical methods, such as Electrical Resistivity Tomography (ERT) and Multichannel Analysis of Surface Waves (MASW), to further validate the interpretation and support sustainable groundwater management and regional planning.

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