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SHEAR WAVE VELOCITY MODEL USING HVSR INVERSION BENEATH BANDA ACEH CITY, INDONESIA

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ABSTRACT: Near-surface shear wave velocity is one of the crucial parameters in earthquake-resistant building development. Therefore, this study aims to map the shear wave velocity profiles in Banda Aceh City-Indonesia, as the city is founded on a relatively thick Holocene sedimentary layer and experienced devastating damage during the 2004 earthquake. The method used in this study is the horizontal-to-vertical spectral ratio (HVSR) method. This method collects single-station microtremor data, which is processed by the HVSR method and then inverted so that a 1D profile of shear wave velocity is obtained. The results show that up to a depth of ~200 meters, the sub-surface layer in the Banda Aceh City is composed of soft to hard soil with shear wave velocity (Vs) values below ~750 m/s. In addition, the site's natural frequency within the city of Banda Aceh is from 0.74 to 1.94 Hz, indicating the presence of a fairly thick and deep soft layer. The combination of relatively low shear wave velocity (Vs) values and low site natural frequencies indicates that the Banda Aceh City area has significant seismic amplification potential. In addition, if the sub-surface soil materials are composed of coarse-grained soils and saturated, most of the soil layers in Banda Aceh City could also potentially experience liquefaction or excessive ground subsidence following an earthquake. A general precaution must be considered in applying the findings of the present study for further studies or actions, as several limitations are inherited in the geophysical method applied in the present study.

Keywords: Banda Aceh, HVSR inversion, shear wave velocity, site characterization, microtremor

1. INTRODUCTION

Near-surface site characterization is one of the important steps in designing earthquake-resistant building structures and other various seismic-related issues. Several parameters resulting from the site characterization process are shear wave velocity (Vs) profile, site natural frequency (f_0), and seismic amplification factor (A_0) [1], [2], [3]. All these parameters are interrelated and play a significant role in understanding soil behavior during earthquakes. Shear wave velocity describes how fast seismic shear waves can propagate through sub-surface layers, while the natural frequency of the site is strongly influenced by the thickness and behavior of the sub-surface sedimentary layer due to shaking, and the amplification factor measures the increase in amplitude of seismic waves as they propagate from bedrock to the ground surface [1], [4], [5]. Understanding the characteristics of these aforementioned parameters is crucial in seismic vulnerability assessment so that any seismic threats can be justified. This seismic risk is critical for densely populated areas, including Banda Aceh, Indonesia, as the city is founded on a relatively thick Holocene sedimentary layer. Following the devastating earthquake and tsunami in 2004, Banda Aceh has started to change rapidly and is undergoing urban development with significant reconstruction and expansion [6], founded on Banda Aceh's young geological deposits. This young age of geological layers suggests an increasing risk of seismic wave amplification. Many researchers have found that local geological conditions certainly influence seismic wave behavior during earthquakes, so a study of local site effects must carefully consider the geological setting at the study site [3], [4], [5], [7], [8].

Various methods for determining shear wave velocity have been proposed in many previous studies, i.e., [9] and [10]. Initially, a correlation using conventional sub-surface investigations, i.e., a number of blow-count of standard penetration test (N-SPT) data, was used to estimate shear wave velocity [9]. Another conventional sub-surface investigation to deduce shear wave velocity is the cone penetration test (CPT) data [10]. Spatial autocorrelation of ambient noise waves was also carried out by Setiawan et al. [11] to estimate the shear wave velocity. Shear wave measurements using active seismic methods such as MASW [12], [13], [14] have been carried out and validated. In the latest development, one of the methods that can be used for site characterization by means of shear wave velocity is the horizontal-to-vertical spectral ratio (HVSR) method. The HVSR method has become one of the acceptable methods in shear wave velocity sub-surface profiling. This method is based on a single-station ambient noise measurement. This method has advantages in terms of simplicity, cost-effectiveness, and non-invasiveness. Furthermore, this method has been applied to a wide range of geological conditions from soft soils to hard rock [15], [16], [17]. The HVSR method produces several results in the form of site natural or predominant frequencies, site amplification factors, and ground seismic vulnerability index, including shear wave velocity profile [1], [15], [17].

The novelty of the present study is in determining the shear wave velocity profile of Banda Aceh using single microtremor or ambient noise measurement. The selected shear wave velocity is the generated profile with the minimum misfit value to the HVSR curve provided.

2. RESEARCH SIGNIFICANCE

This research aims to characterize the sub-surface conditions, i.e., shear wave velocity of Banda Aceh City, Indonesia. The results of the present study can later be used in various studies or further research, such as site classification and seismic response, design and construction, geotechnical exploration, and geophysics. The findings of this research are crucial as basic data in site response analysis studies and soil-structure interaction studies.

3. GEOLOGICAL SETTING

The city of Banda Aceh is located in Aceh Province (The northern tip of Sumatra Island), as shown in Figure 1. Geologically, the landscape of Banda Aceh was originally a basin area of Krueng Aceh, so this area is a zone composed of relatively young deposits of sedimentary material [18], [19]. Several studies have also mentioned that Banda Aceh is composed of a thick sediment layer up to a depth of more than 200 m [18], [19]. These Quaternary sedimentary deposits, called alluvial deposits (Figure 1), consist of gravel, sand, silt, and clay. In addition, the Krueng Aceh basin is also filled with Holocene marine and fluvial sedimentary material. On east and west sides of the Krueng Aceh basin are flanked by two faults that are part of the great Sumatran fault. The segment of the Seulimeum Fault in the east and the segment of the Aceh Fault in the west. Several studies suggested the Krueng Aceh basin to be classified as a graben-type basin [19], [20], [21]. The segment of Aceh Fault is a fault formed in the Jurassic to Cretaceous period as a result of the accretion of oceanic and continental plates that are part of the Woyla Group, while the segment of Seulimeum Fault was formed during volcanic processes [18], [19].

In terms of seismicity, the two segment faults, i.e., Seulimum segment and Aceh segment, provide the greatest seismic threat to the city of Banda Aceh [22]. Banda Aceh also has another seismic risk, which is the megathrust zone located ~250-300 km west of Banda Aceh. This seismic zone has been very active recently. One of the major earthquakes along this zone was the 2004 earthquake with a magnitude of 9.3 Mw [23], [24], [25], [26].

4. METHODS

Microtremor measurements were conducted at 16 locations across Banda Aceh City. The measurement locations are shown in Figure 1. Data processing was performed using the horizontal-to-vertical spectral ratio (HVSR) method. The HVSR method is a method that compares the Fourier amplitude spectrum of the horizontal and vertical components [27], [28], from which the HVSR curve is obtained. The resulting HVSR curve was then inverted to obtain a shear wave velocity profile.

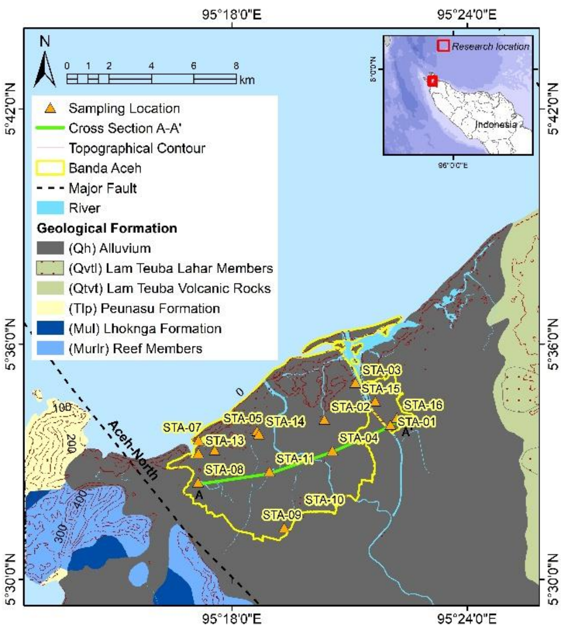

Fig.1 Geological Maps of Research Location Modified from Bennet et.al [18]

4.1 Parameterization for inversion

The main input data required in the inversion process are the HVSR curve and the predetermined sub-surface initial model. The HVSR curve was obtained using the H/V tool from Geopsy software. While the predetermined preliminary model was obtained from borehole data derived mainly from the research of Rusydy et.al [19]. The predetermined sub-surface initial model is described in Table 1. A total of 6 sub-surface layers in this predetermined model is proposed. The initial values of compression wave velocity (Vp), Poisson ratio (nu), and density (rho) are obtained using the default values given in the software used. The initial value of shear wave velocity (Vs) is based on Rusydy et al [19], regional geological conditions, and the classification of SNI 1729: 2019 [18], [19], [29].

Table 1. Initial stratigraphic model of the layer

Layer	Thickness	Input Parameter	Description
1	~30 m	Vp = 200 – 3000 m/s nu = 0.1 – 0.5 Vs = 50 – 750 m/s Rho = 0 – 2000 kg/m^3	Sand
2	~10 m		Clay
3	~10 m		Sand
4	~30 m		Clay
5	~20 m		Sand
6	~40 m		Sandy Clay

4.2 Misfit selection criteria

In the inversion of the HVSR curve, we generated up to thousands of shear wave velocity models. In the present study, we select the shear wave velocity model based on the least misfit value. The minimum misfit value is chosen to obtain the sub-surface model most consistent with the observed HVSR data. We assume that the misfit value reflects how much difference there is between the obtained measured HVSR curve and the theoretical curve generated from the proposed stratigraphic model. The smaller the difference between the two curves, the lower the misfit value, so that the model can be considered more representative of the real geological conditions [14], [30], [31].

5. RESULTS AND DISCUSSIONS

5.1 Shear wave velocity profile

The results of the HVSR curve inversion by means of a 1D shear wave velocity profile up to 200 m depth at 16 locations are shown in Figures 3 to 5. Various sub-surface profiles are suggested. As expected, the overall inversion results show a shear wave velocity of less than 750 m/s. Based on the classification of SNI 1726: 2019 [29], the sub-surface of Banda Aceh City to a depth of 200 m is composed of soil layers [soft soil (SS) for Vs < 175m/s, medium soil (MS) for 175 m/s ≤ Vs < 350m/s, and hard soil (HS) for 350 m/s ≤ Vs < 750 m/s], as shown in Figures 3 to 5 below.

In general consensus, the shear wave velocity, Vs, has a close relationship with the depth of the layer, where the shear wave velocity will increase as the depth increases. This is due to the pressure of the upper layer that causes the layer below to become denser (overburden pressure) [32]. In the case of Banda Aceh City, the increasing shear wave velocity, Vs aligned with the depth is shown at STA-07 in Figure 4, STA-15, and STA-16 in Figure 5. However, under certain circumstances, the increase in depth does not always cause an increase in shear wave velocity. Many locations, such as STA-01, STA-02, STA-03, STA-04, STA-06, STA-08, STA-09, STA-10, STA-11, STA-12, STA-13, and STA-14, within the study area suggest varying (go up and down) shear wave velocity values as the depth increased. This incident can occur due to the presence of soil layers that are deposited in a very fast process, between soil layers that experience a slow and gradual deposition process.

To get a better understanding of the sub-surface shear wave velocity across the Krueng Aceh basin, we developed a cross-section profile. Figure 6 displays a cross-section of the sub-surface layer drawn lengthwise from southwest (SW) to northeast (NE) in Banda Aceh City. The line of the cross-section is shown in Figure 1. The cross-section displays interpolated shear wave velocity data from several observation points (STA-08, STA-11, STA-04, STA-01, and STA-16). The section shows that there are some soft layers (SS) deposited between denser layers (MS-HS). In addition, soft layers (SS) were also found at greater depths. Furthermore, as mentioned in the geological setting section, the city of Banda Aceh is a basin with fluvial and marine depositional environments [17]. Therefore, the depositional environment can change depending on global seawater conditions. This causes the basin to be filled with alluvial material that varies from clay to sand, which can also cause the formation of sedimentary lenses due to this instability [19]. The formed sedimentary lens may cause a localized decrease or increase in shear wave velocity at certain locations.

The results of this study were also compared with the study conducted by Asrillah et al. [33] and Rusydy et al. [19]. The study conducted by Asrillah et al. [33] obtained maximum shear wave velocities up to ~958 m/s with depths reaching ~650 m. Asrillah et al. [33] suggested that the alluvium layer is found at a depth of 70-100 m with shear wave velocities around ~400 m/s. Then the next layer is the diluvium layer with a thickness of ~40 m below the alluvium layer with a shear wave velocity of ~600 m/s. Thus, in general, the results of the present study show similar conclusions to the findings of Asrillah et al. [33] where up to a depth of ~200 m, the layers found are still sediment or soil. The difference found lies in the shear wave velocity value. However, a disagreement is suggested between the present study and Asrillah et al. [33] on the general shear wave velocity profile. Asrillah et al. [33] presented a linear increase in shear wave velocity profile as the depth increases. The present study found that the shear wave velocity profile obtained varies (not always increasing with depth). This fluctuating shear wave velocity profile is in reasonably good agreement with Rusydy et al. [19]. Overall, the shear wave velocity profiles developed in the present study provide satisfactory results in accordance with the initial predictions and regional geological conditions of Banda Aceh City [17].

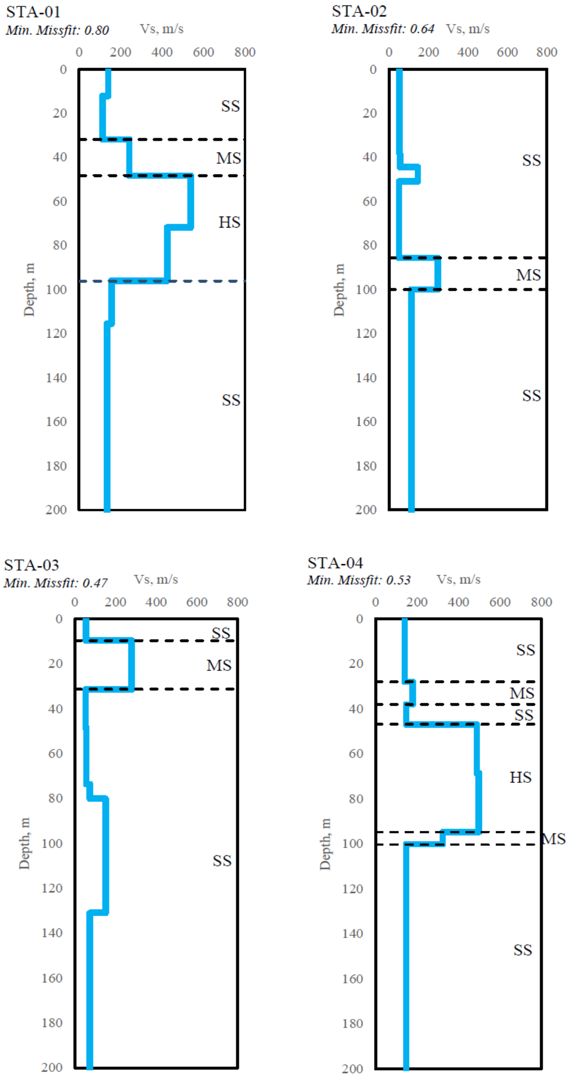

Fig.3 Shear wave velocity curve with minimum misfit based on the inversion of the HVSR curve at STA-01, STA-02, STA-03, and STA-04.

For other seismic-related studies, such as seismic hazard analysis, site response analysis, and various other studies, it is necessary to classify sites based on the average shear wave velocity up to a depth of 30 m (V_{s30}). The V_{s30} map of the present study is shown in Figure 7. Most locations in the city of Banda Aceh are founded on soft to medium-dense soils (~V_{s30} is less than 350 m/s). Soft soils tend to increase the amplitude of earthquake waves, especially at long periods (low frequencies). As a result, this can cause greater damage to tall structures [34].

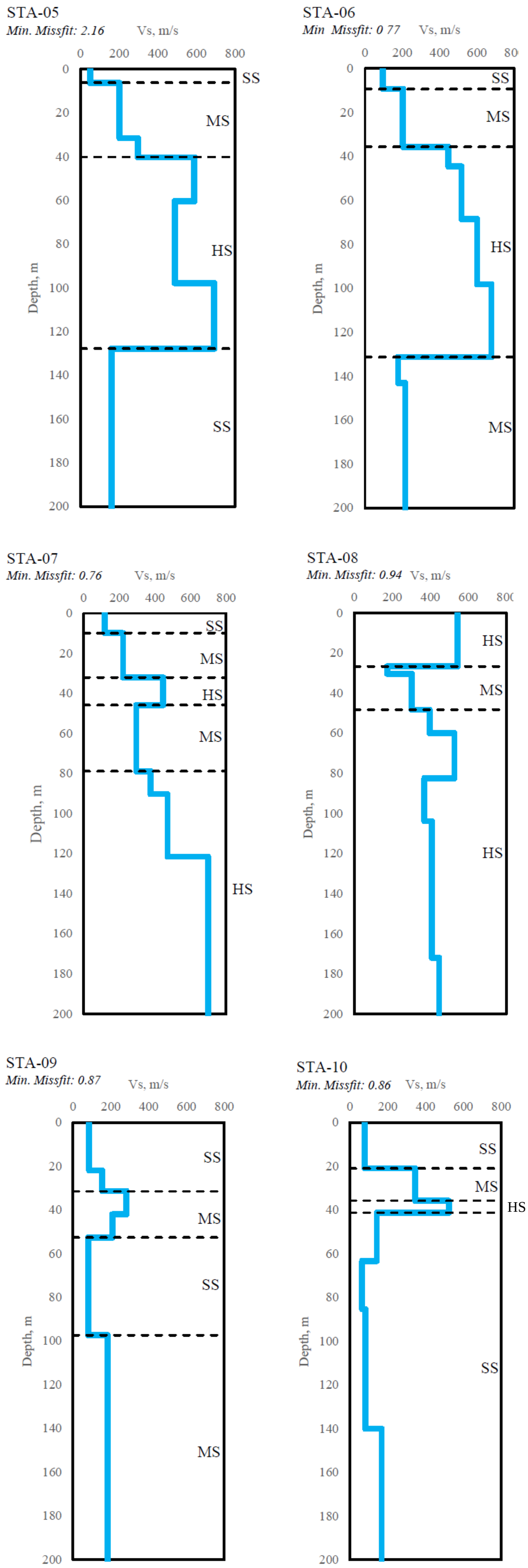

Fig.4 Shear wave velocity curve with minimum misfit based on the inversion of the HVSR curve at STA-05, STA-06, STA-07, STA-08, STA-09, and STA-10.

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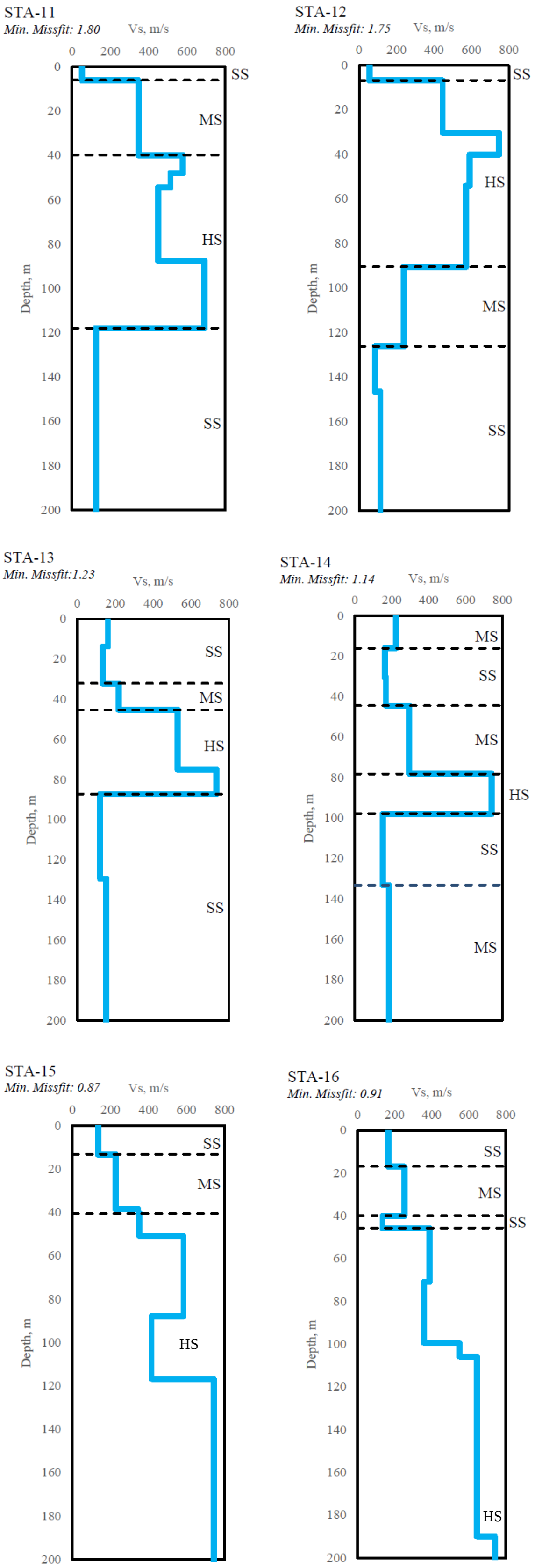

Fig.5 Shear wave velocity curve with minimum misfit based on the inversion of the HVSR curve at STA-11, STA-12, STA-13, STA-14, STA-15, and STA-16.

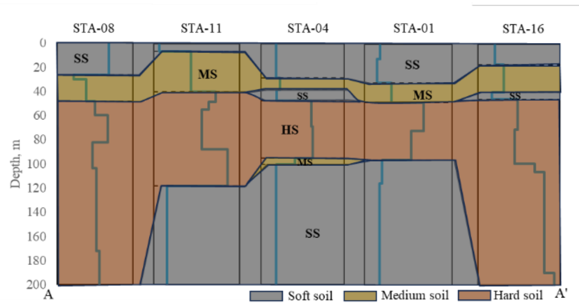

Fig.6 Cross-section of shear wave velocity in Banda Aceh City

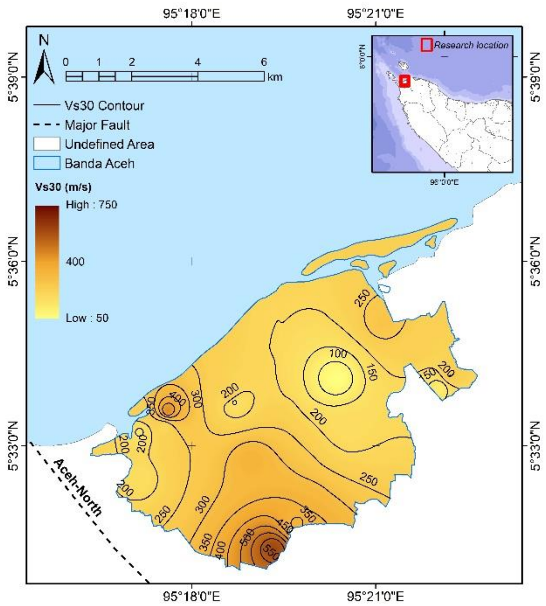

Fig.7 Map of average shear wave velocity values up to a depth of 30 m, V_{s30}.

The soft to medium-dense soils (~V_{s30} is less than 350 m/s) within the city of Banda Aceh require extra attention from stakeholders in building any structure in the city. In terms of design, the seismic coefficient in the structural design should be increased to account for soil amplification. In addition, low V_{s30} values indicate the potential for liquefaction, especially if the constituent layers are saturated and coarse-grained soils. In addition to liquefaction, the liquefiable soils can also increase the excessive ground settlement during an earthquake.

5.2 Site predominant frequency

Another output of analyzing microtremor data using the HVSR method is site predominant frequency (~site natural frequency). Site natural frequency provides important information about the sub-surface characteristics [35]. In general, the natural frequency obtained ranges from 0.74 to 1.94 Hz. This finding is well agreement with the study by Setiawan et.al [3] who obtained site predominant frequency of the Banda Aceh City in the range of 0.2 - 1.1 Hz [3].

Based on the soil classification proposed by Kanai [36], a site with a frequency of less than 2.0 Hz is classified as a class IV site. This class IV site is characterized as a site composed of alluvial deposits in the deltaic environmental setting and estimated thickness of more than 30m [35]. This result is also found in the regional geological conditions of Banda Aceh City, which suggests that the city is a basin composed of alluvial or sedimentary deposits [18]. In addition, the drilling also revealed that alluvial or sedimentary deposits are still found to a depth of more than 200 m [18].

Low-frequency sites (having a very thick soft layer) have two dynamic consequences in seismic-related hazards, such as the amplification of waves propagating to the surface, and the duration of perceived vibrations tends to be longer. These consequences cause medium-high-rise buildings and other utility infrastructure that have similar or relatively close vibration periods will experience greater peak accelerations and larger lateral displacements [12], [13].

5.3 Limitations

A general precaution must be considered in applying the findings of the present study for further studies or actions, as several limitations are inherited in the geophysical method applied in the present study. The limitations are outlined, as follows: non-uniqueness (geophysical method tend to propose several mathematical solutions for sub-surface interpretation), resolution (the present study uses a very limited data), noise (the applied geophysical method in the present study always be affected by data bias during the field measurement), and applicability in complex geological conditions (a site specific complex sub-surface geological characteristics will contribute to the discrepancy the results of the HVSR inversion process in the present study).

6. CONCLUSION

The present study reveals that the sub-surface conditions to a depth of about 200 meters in Banda Aceh City are composed of sedimentary materials with soft to hard soil characteristics, with shear wave velocities (Vs) of less than 750 m/s. Based on these characteristics, it can be concluded that the soil in the area is still dominated by unconsolidated to semi-consolidated sediments. The site's predominant or natural frequency within the study site, in the range of 0.74 to 1.94 Hz, indicates the presence of deep and thick soft layers, which tend to resonate to low-frequency earthquake waves. These characteristics indicate a high potential for local amplification, which not only affects the increase in vibration amplitude but also extends the duration of shaking. This can have serious impacts on multi-story structures and other infrastructure with comparable vibration periods, as they are at risk of excessive dynamic response. The limitations applied method in the present study should be considered prior to the application of the findings of the present study for further actions.

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