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# Ambient noise analysis for characterizing sub-surface dynamic parameters

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**Abstract.** Ambient noise analysis of horizontal to vertical spectral ratio (HVSR) method has been used widely to provide reliable estimates of the site fundamental frequency and to constrain the inversion of near-surface shear wave velocity. The present paper focuses on the site measurement using the aforementioned analysis by means of the HVSR method for characterizing sub-surface dynamic parameters in the City of Banda Aceh, Indonesia. A Guralp CMG-6TD broadband seismometer was used in this study to cover a wide frequency range from 0.033 Hz to 50 Hz in standard operation. The instrument was deployed at two different sites (i.e. Location#1 of Blang Padang and Location#2 of Stadion Dirmutala) in the City of Banda Aceh for at least 2 hours for ambient noise recording. This continuous of 2 hours' microtremor time series was separated into 30 minutes record from which the site fundamental frequency and shear wave velocity of the measured site were deduced. The later sub-surface dynamic parameter was validated using another technique of reflection seismic. This investigation suggests the fundamental frequency of 0.45 Hz at Location#1 and of 0.65 Hz at Location#2. The estimated shear wave velocity of the top 30 m,  $V_{s,30}$  of this investigation is 165 m/s at Location#1 and 156 m/s at Location#2. Both the site fundamental frequency and shear wave velocity are important for infrastructure design in the high seismic region of Banda Aceh, Indonesia.

## 1. Introduction

The velocities of seismic waves are much faster in rocks than in soils. Since the same amount of kinetic energy will propagate in rocks and soils, the amplitude of the seismic waves will strongly expand when the waves pass from rock through the soil layer. This amplitude expansion causes that the ground displacement at soil sites is usually greater than at rock sites. In some conditions, the ground shaking duration at soil sites also tends to be longer than at rock sites, which is also the result of a frequency transformation. These large ground displacement and long seismic duration are dangerous to any infrastructures founded on it [1,2,3]. Two sub-surface dynamic parameters, which are well accepted to contribute to the structural damage during a seismic event, are site fundamental frequency and the near-surface shear wave velocity profile. Ambient noise analysis of horizontal to vertical spectral ratio (HVSR) method has been used widely to provide reliable estimates of these site fundamental frequency and near-surface shear wave velocity [3,4,5]. Characterization of the sub-surface dynamic parameters based on single microtremor measurement method (sMSM) was carried out at two sites in the city of Banda Aceh, Northern Sumatra, Indonesia. There are several advantages

of the sMSM, i.e. simple, non-destructive, low cost and very feasible for sub-surface investigation in an urban area. This sMSM for seismic related studies have been applied by [6,7,8,9,10]. Empirically, there is a robust relationship between the structural seismic damages of buildings and their near-surface geological setting [11,12,13]. In the case of the structural frequency matches the fundamental frequency of the ground where the structure is founded, resonance will occur [1,2]. It is demonstrated in 1985 Mexico earthquake [1,3], 1995 Kobe earthquake [2], and 1999 Izmit earthquake [14]. Thus, characterizing the ground dynamic parameters is important in order to mitigate the seismic disaster and understand how the structure behavior during a seismic event.

## **2. Seismic source zones around the city of Banda Aceh**

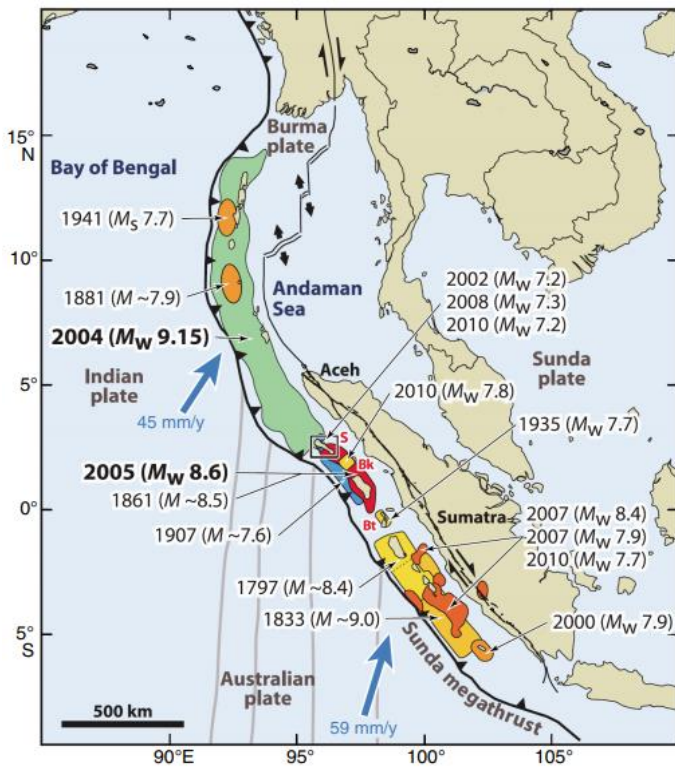
Two main seismic source zones of the tectonic subduction and the great Sumatran fault have been identified around the city of Banda Aceh. The tectonic subduction zone is the north-northeast oriented convergence subduction zone between the Indo-Australian plate and the Eurasian plate with the speed rate of up to 60 mm per year [15]. This zone has triggered several strong seismic events ( $\geq 8.0$ ), i.e. 1861 Nias earthquake, 2004 Sumatra-Andaman earthquake, and 2005 Simeulue earthquake [16,17]. These earthquake's slips are along the megathrust sections between the Indo-Australian and Eurasian plates (Figure 1). The 2004 and 2005 earthquake events were among the great seismic events to be studied using advanced seismological techniques. The later seismic source zone recognized around the city of Banda Aceh is the Great Sumatran Fault (GSF), as shown in Figure 2. The city of Banda Aceh is potentially exposed to significant seismic hazard of this major right-lateral strike-slip fault. The GSF is capable to cause up to  $M=7.9$  earthquake [18]. Historically  $M=7.7$  earthquake was occurred along this GSF in 1892 near the city of Sibolga ( $\pm 570$  km southeast of Banda Aceh) (cf. [17]). Furthermore, the city of Banda Aceh is built on up to 200 m thick alluvium sequences [19]. Any structures founded on thick alluvium poses a very high seismic vulnerability [1,3]. Therefore, sub-surface dynamic parameters study of Banda Aceh-Indonesia is urgently required for the city of Banda Aceh as the city is at risk for severe earthquake [20]. Understanding Banda Aceh's ground surface behavior is essential for developing the city's infrastructures.

## **3. Methods**

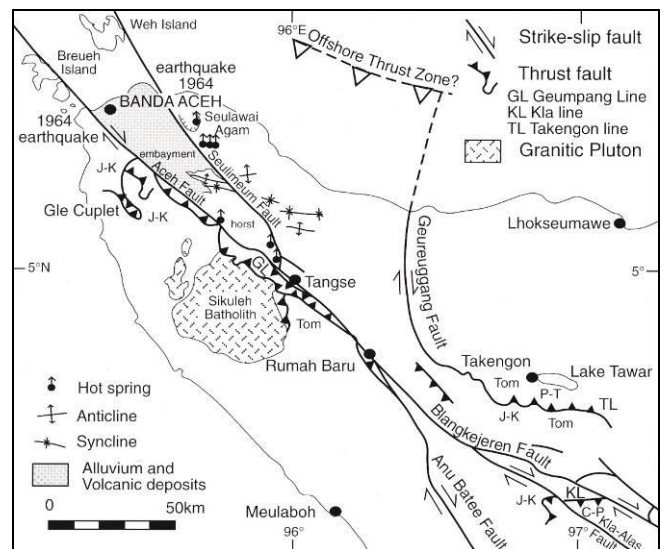
The following sections describe the deployed equipment, data acquisition process, and data analysis used in this study, which is briefly explained, as follow:

### *3.1. Equipment*

The seismometer used for the microtremor measurement in this study is the Guralp CMG-6TD/Broadband (0.033 Hz to 50 Hz in standard operation), as shown in Figure 3. It is a digital three-axis seismometer, which can record the north/south, east/west and vertical components of ground movement simultaneously. This broadband seismometer is perfectly suited for quick and easy installation in medium noise sites. The instrument offers an integrated 24-bit digitiser and a configurable output and ultra-lightweight (3 kg) and waterproof characteristics. Detailed main features of this seismometer are summarized in Table 1. The site installation of this equipment is shown in Figure 4.



**Figure 1.** Tectonic setting of the Sumatran subduction zone showing major recent and historic plate boundary earthquake ruptures and their magnitudes (from [21], and references therein). Black lines = faults, grey lines = fracture zones.



**Figure 2.** Faults around the city of Banda Aceh [22].



**Figure 3.** Guralp 6TD/Broadband seismometer, break out cable, GPS antenna, and battery for power supply



**Figure 4.** Illustration of installation of the deployed equipment

**Table 1.** Several important characteristics of the used seismometer

Parameter	Description	Remarks
Velocity output	30 s (0.03 Hz) to 100 Hz	Guralp CMG-6TD integrated digitiser
Output sensitivity	2400 V/ms <sup>-1</sup> (2*1200 V/ms <sup>-1</sup> ) differential output	
Self-noise	-172 dB (Relative to 1[m/s <sup>-1</sup> ] <sup>2</sup> Hz <sup>-1</sup> )	
Power supply	11 to 28V DC, typically 7 mA @12 V	
Power consumption	0.93W without GPS or Ethernet at 12V DC	
Dimensions	153 mm diameter, 173 mm height (excluding handle)	
Weight	3.0 kg	
Temperature range	-20 ... +65 °C	

### 3.2. Data acquisition

The field ambient noise data were recorded from 15:40 pm on 20 April 2019 to about 01:00 am on 21 April 2019. The general weather during the data acquisition was calm with no strong winds or rain. Measurement locations were at near downtown of the city of Banda Aceh with Latitude of 05.549396 deg N and Longitude of 95.312956 deg E, as shown in Figure 5a (called Location#1) and at eastern of the city of Banda Aceh with Latitude of 05.567211 deg N and Longitude of 95.340452 deg E, as shown in Figure 5b (called Location#2). Precaution was carried out prior to the data acquisition to avoid man-made holes (i.e. infills) and other underground structures. The field microtremor data collection at Location#1 was carried out from 22:45 PM on 20 April 2019 until about 02:00 AM on 21 April 2019. The field activity at Location#2 was started from 15:40 PM until 18:00 PM on 20 April 2019. At least 2 hours of ambient noise data were recorded at both Locations#1 and #2. A summary of the field data acquisition is presented in Table 2.

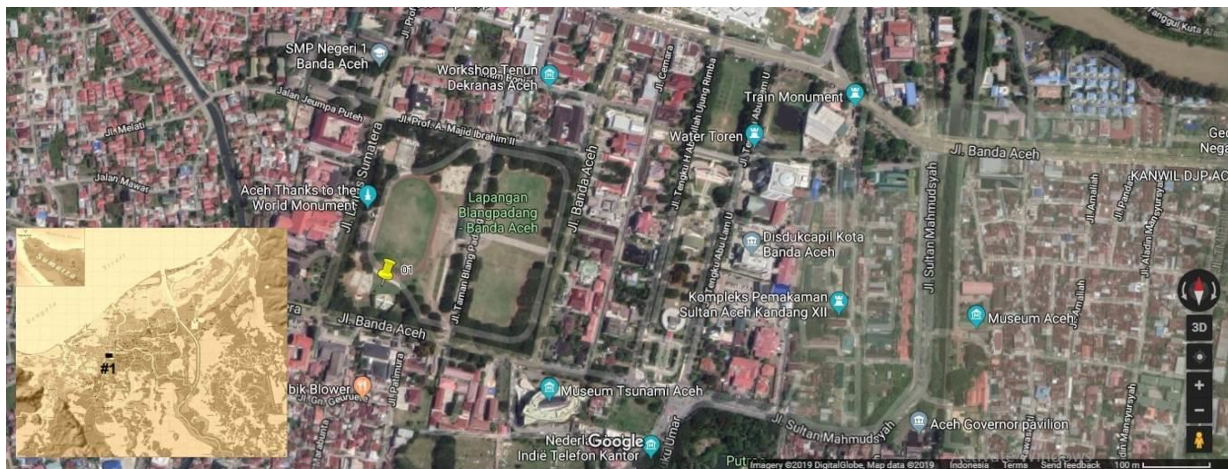
### 3.3. Data analysis using horizontal vertical spectral ratio (HVSr)

#### 3.3.1. HVSr curve

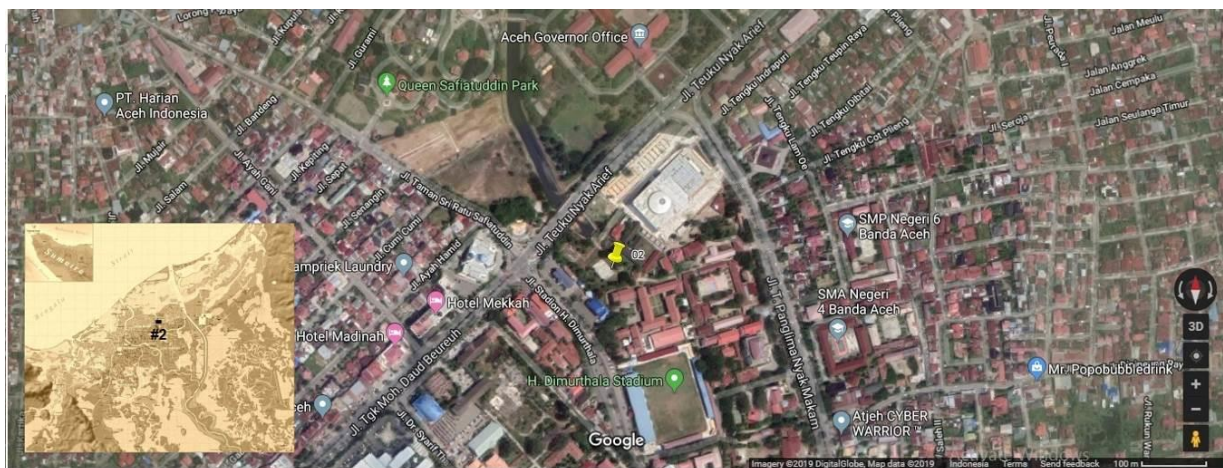
The HVSr method is used to obtain the site fundamental frequency since introduced in 1989 by Nakamura [6]. The method focuses on the analysis of the spectral ratio of the Fourier amplitude spectrum of the horizontal (H) over vertical (V) components of the ambient noise particle movement velocity from which the HVSr curve and fundamental frequency of the measured site are estimated. Guidelines of data analysis using the HVSr method and interpretation of the result can be found in [23]. Several researchers i.e. [6,7,24] have successfully applied the HVSr method to compute the site fundamental frequency.

#### 3.3.2. Inversion of the shear wave velocity

The measured HVSr curve and the estimated site fundamental frequency were used to obtain the sub-surface shear wave velocity profile of the measured site [25]. A tentative stratigraphic constraint is used in the inversion process by setting the layer depths, compression wave velocity, shear wave velocity, poisson ratio, and density, in the neighborhood algorithm inversion code of Dinver [26] and [27]. The input parameters for the inversion adopted in this study are presented in Table 3 based on the studies [28] and [29]. Subsequently, the input parameters jointed with the obtained HVSr curve were used to generate at least 5,000 (i.e. 5,193) shear wave profile models, from which the best 20 shear wave velocity profile models are extracted and selected to propose the shear wave velocity profile of the measured site. The best 20 models are associated with the lowest 20 misfit inversions from the measured HVSr curve.



(a)



(b)

**Figure 5.** Ambient noise measurement sites at (a) near the downtown of the city of Banda Aceh, and (b) eastern of the city of Banda Aceh (yellow pins). The inserted small general maps show the locations on the Krueng Aceh river delta plain in the north of Sumatra.

**Table 2.** A summary of the field data sheet.

Parameter	Location#1 (Blang Padang)	Location#2 (Stadion Dirmutala)
Latitude	05.549396 deg	05.567211deg
Longitude	95.312956 deg	95.340452 deg
Sensor type	Guralp CMG-6TD	Guralp CMG-6TD
Sample frequency	100 Hz	100 Hz
Weather conditions	No wind; no rain; Approx. temperature 27 degrees	Weak wind; no rain; Approx. temperature 32 degrees
Ground type	Concrete pavement	Concrete pavement
Artificial ground/sensor coupling	None	None
Urbanization	Open field	Basketball field
Continuous noise sources	None	None

**Table 3.** Input parameters for the inversion

Layer No.	Depth (m)	Compression wave velocity (m/s)	Poisson's ratio	Shear wave velocity (m/s)	Density (kg/m <sup>3</sup> )
Layer#1	1 – 50	200-500	0.2 – 0.5	100-350	1800-2000
Layer#2	20 – 100	200-800	0.2 – 0.5	150-500	1800-2000
Layer#3	70 – 300	200-800	0.2 – 0.5	150-500	1800-2000
Layer#4	150 – 400	400-1000	0.2 – 0.5	150-500	1800-2000
Layer#4	>400	700-5000	0.2 – 0.5	300-800	1800-2000

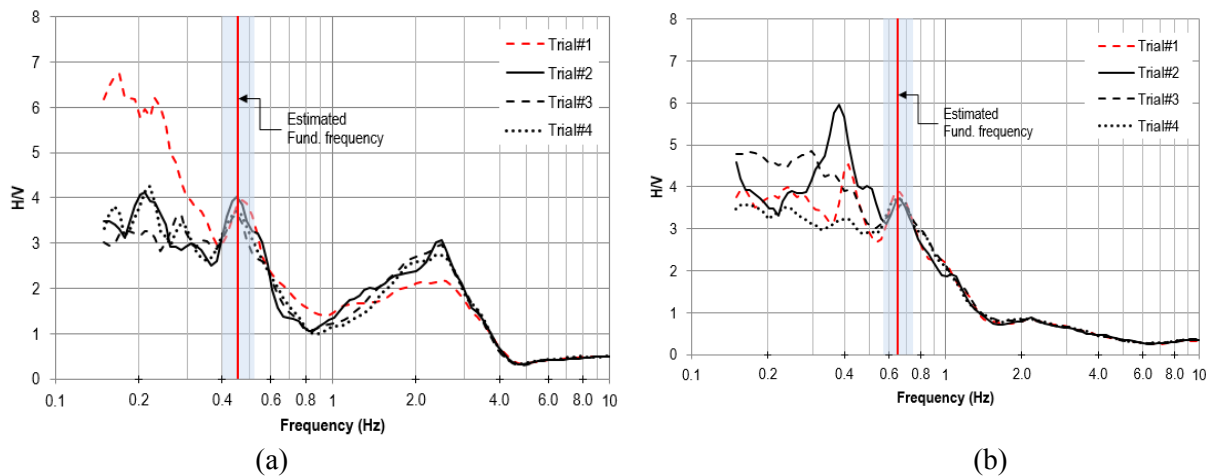
Note: Layer#4>Layer#3

**4. Results**

The HVSR curve, estimated site fundamental frequency, and developed shear wave velocity profile of the measured sites are presented. A brief discussion of the result is elaborated, also.

*4.1. HVSR curve and site fundamental frequency*

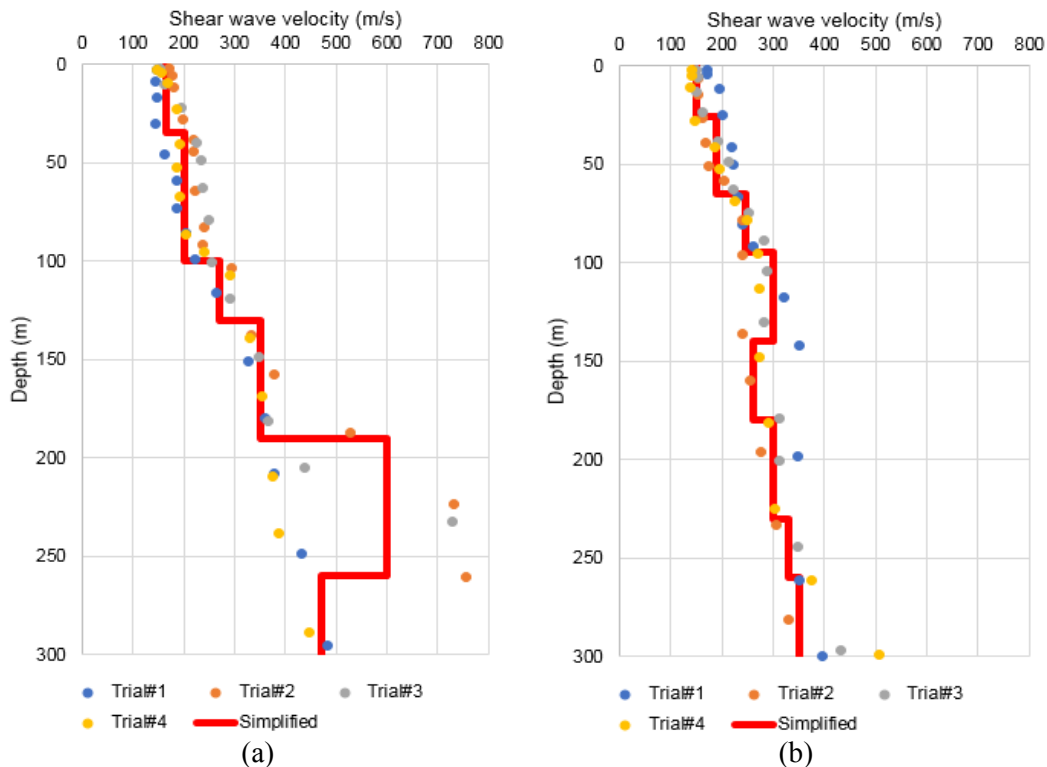
The results of the HVSR technique by means of site fundamental frequency of the measured sites which are Location#1 at Blang Padang and Location#2 at Stadion Dirmutala of Banda Aceh-Indonesia are presented. The HVSR curves of the two investigation sites are shown in Figures 6a and 6b. The site fundamental frequency obtained from the HVSR analysis at Location#1 estimates a frequency of 0.45 Hz. The site fundamental frequency obtained from the HVSR analysis at Location#2 is estimated at 0.65 Hz and indicates a secondary peak at nearly 2.7 Hz, which is not consistent over the four functions.



**Figure 6.** HVSR curves and estimated site fundamental frequencies at (a) Location#1, and (b) Location#2

*4.2. The shear wave velocity profile*

The inverted shear wave velocity-depth profiles using the neighborhood algorithm at both Locations #1 and #2 are presented in Figures 7a and 7b. The average of the four inversion trials for both Locations #1 and #2 are shown by a blocked mean function as red lines in Figures 7a and 7b. For Location#1, the simplified shear wave velocity-depth function at this location is gradually increasing from the ground surface to about 190 m in depth below the ground level (bgl), where a sharp increase to 600 m/s is visible (Figure 7a). Below 260 m bgl the velocity decreases to 480 m/s. The strong scattering of the inversion results in the interval 190-260 m probably indicates instability of the inversion algorithm (more about this in the discussion). For Location#2, the shear wave velocity inversion results are in a small scattering range up to 300 m bgl and show a gradually increase of the simplified shear wave velocity from 150 m/s at the surface to 350 m/s 300 m bgl.



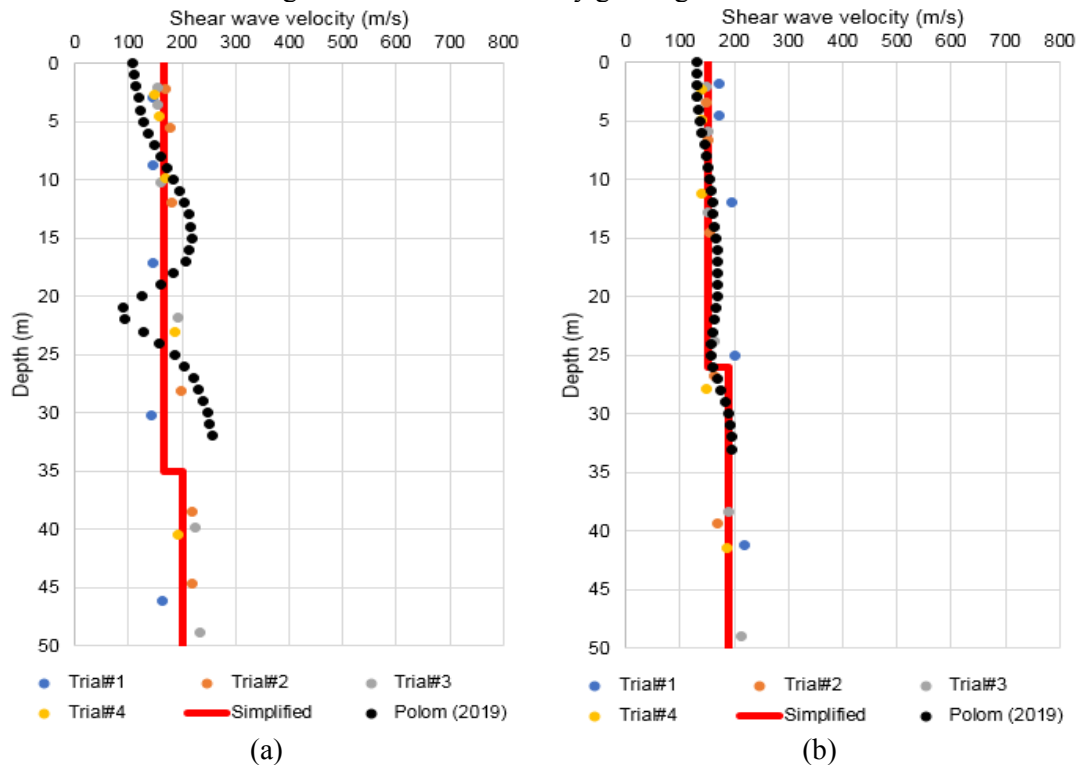
**Figure 7.** Inversion result by the neighborhood algorithm method of the shear wave velocity profiles at (a) Location#1 and (b) Location#2

#### 4.3. Discussion

The studies [30,31,32] have investigated the relationship between the HVSR curve peak(s) and the resonance frequency of the shear wave. The results of the investigation can be summarized as follows: 1) In the case of a high-impedance contrast at the investigation site, the HVSR of the body S-waves always reveals a peak around the fundamental shear wave frequency; 2) In the case of a site consisting of a horizontally stratified media, the HVSR presents also peaks at the harmonics of the fundamental frequency; 3) In the investigation site case of a high-impedance contrast composed of a horizontally stratified media, the amplitude of the HVSR peak of the lowest frequency represents the shear wave amplitude amplification at the site. These findings are very useful for interpreting this study HVSR results. The HVSR curves at Location#1 indicate two peaks, which suggests a complex sub-surface layer structure at the site. Furthermore, the inversion shows unstable results in the depth range 190-260 m bgl. This complex sub-surface structure at Location#1 suggested by this study (Figure 7a) is also reported by Polom [29] (pers. communication, 2019), as shown in Figure 8a. The two peaks of 0.45 Hz and 2.7 Hz of the HVSR curve suggest the existence of two different impedance contrasts at different depths. In the case of this study, the first peak can be correlated to a deep stiff layer at nearly 18 m depth and the second one to a shallow stiff layer at nearly 140 m in depth [23,33,34]. The results of the two study locations suggests that the site fundamental period of the city of Banda Aceh is of  $\approx 1.53$  s to  $\approx 2.22$  s regarding the site fundamental frequency range of 0.45 and 0.65 Hz at the two locations. Therefore, seismic site amplification is suggested for standard reinforced concrete buildings >50 meters height in the city of Banda Aceh (see [35] and [36]). This general suggestion should be treated carefully as the frequency of the building is strongly depends on the building detailed structure. Recently, it is well accepted that a further amplification will occur when the building period is equal to or close to the ground period. The inverted top 30-meter shear wave velocity,  $V_{s,30}$  models of this study are validated using [29]. In 2005 shear wave velocity measurements by the shear wave reflection seismic method were carried using a Geometrics GEODE recording system at both Locations #1 and



#2 in the frequency range 20-120 Hz [29]. The comparison is shown in Figure 8. Even though the range of measurement frequencies of the two methods are strongly different, a very good agreement is presented for Location#2 (Figure 8b). This study suggests  $V_{s,30}$  of 165 m/s instead of [29] of 174 m/s at Location#1. The  $V_{s,30}$  at Location#2 is estimated of 156 m/s instead of [29] of 162 m/s. Assuming a criterion of a quarter wavelength for the smallest structure resolution, i.e. 91 m for Location#1 and 60 m for Location#2 the resulting differences are in a very good agreement.



**Figure 8.** Comparison of the top 30-meter shear wave velocity,  $V_{s,30}$  between this study and [28/26] at (a) Location#1 and (b) Location#2

## 5. Conclusion

Various studies have demonstrated the advantages and applicability of single point microtremor measurement and analysis for characterizing sub-surface dynamic parameters i.e. the site fundamental frequency and near-surface shear wave velocity. This single microtremor measurement and analysis have been carried out at two different locations in the city of Banda Aceh, which is highly vulnerable to seismic hazard. This study suggests site fundamental frequencies of 0.45 Hz and 0.65 Hz at the measured sites. This study also proposes  $V_{s,30}$  of 165 m/s at Location#1 and of 156 m/s at Location#2. Therefore, it can be concluded that single microtremor measurement can provide easy, affordable and fast to obtain sub-surface dynamic parameters in the region of Banda Aceh city.

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