SHARE WAVE VELOCITY MODEL TO A DEPTH OF 30 METER (Vs30) USING *HORIZONTAL VERTICAL TIME FREQUENCY ANALYSIS* (HVTFA) METHOD

Meta N. Syafitri[1], Syawaldin Ridha[2] Sukir Maryanto[3], Agustya Adi Martha[4]
[1, 2, 3] *Universitas Brawijaya, Jl. Veteran, Malang 65145*
[2]*BMKG Office Tretes, Jl. Melaten Lor, Plintahan, Pandaan Sub-District, Pasuruan 67156*
(syawaldin.ridha@gmail.com)
[4] *BMKG Office Jakarta, Jl. Angkasa I, No.2 Kemayoran, Jakarta Pusat 10610*

ABSTRACT

A share wave velocity model to a depth of 30 meter (vs30) can be used to find the type of the ground as a preventive action against earthquake disaster mitigation. Vs30 is obtained from the inversion of ellipticity curve using HVTFA method. HVTFA method is a method that can minimize the love curve in the ellipticity curve. Therefore, a more reliable share wave velocity can be obtained. It is necessary to find reliability of a model in a further research. The objectives of this research were to find the reliability of HVTFA and HVSR methods and determine the reliability of vs30 model from the result of inversion of Rayleigh-wave ellipticity curve using HVTFA method with duration of microtremor measurement of 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours. Data used in this research were microtremor data. The microtremor data were processed using HVTFA and HVSR method in *Geopsy* software to find the ellicpticity curve. Next, the inversion of ellipticity was carried out in *dinver* software to obtain the share wave velocity model. After that, the error value from the model was calculated using vs%Miss, Boun%Miss, Ev, and Eb. The error value of HVTFA method still met the requirement of reliable model, but not the error value of HVSR method. The high error value in HVSR method was found in Bound%Miss and Eb. It meant that the share wave velocity of HVSR method had a high error value in the estimation of surface depth and thickness. Therefore, HVTFA method produced a more reliable vs30 model than HVSR method. In addition, the velocity model of HVTFA method from microtremor data with duration of 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours also had reliable model.

Keywords : Vs30 model, microtremor, HVTFA, HVSR, ellipticity curve

1. INTRODUCTION

Indonesia is a country where earthquake is frequently occurred. The risk of the earthquake is damage to buildings causing casualties and material losses. In order to reduce the risk, it is important to make preventive mitigation actions. One of which is to make earthquake resistant building. Before making the earthquake resistance building, we need to know the characteristic of the soil where the building is going to be made. The soil characteristics can be found in table SNI 1726-2012 classifying the soil based on the mean of share wave velocity to a depth of 30 meter called as vs30. Consequently, the seismic hazard can be predicted (Kanli, dkk).

One of methods to obtain vs30 values is by share wave velocity model with inversion of Rayleigh-wave ellipticity curve from microtremor data. The Rayleigh-wave ellicpticity curve is obtained by performing *Horizontal Vertical Time Frequency Analysis* (HVTFA). The result of this inversion is the share wave velocity on the depth. HVTFA is used to extract Rayleigh-wave ellipticity curve from microtremor data and minimize the love wave because it only affects horizontal component of microtremor data, so it was worried that over-estimation on H/V amplitude would happen (Knapmeyer-Endrun, dkk. 2017).

According to Antashband and Esfahanizadeh (2012) duration of reliable microtremor measurement for vs30 model resulted from the inversion of Rayleigh-wave ellipticity curve obtained from the processing of HVTFA data was seven hours. However, there were many microtremor data that was less than seven hours and the measurement for seven hours was a long time.

Example from the micrometer measurement data with duration that was less than seven hours was micrometer data with duration of 0.5 hours that previously was used for *Horizontal to Vertical Spectral Ratio* (HVSR) processing. Therefore, it is important to perform a research testing the reliability of a model from microtremor data with duration of less than seven hours, so the measurement duration becomes more effective. Consequently, the objectives of this research are to find the reliability of HVTFA and HVSR methods and determine the reliability of vs30 model resulted from the inversion of ellipticity curve using HVTFA method with duration of microtremor measurement of 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours.

2. BASIC THEORY

Microtremor

Microtremor is the ambient vibration of the ground caused by human activities, such as traffic activity in the surface of the earth, and sources of ground vibration caused by natural factor, such as interaction between the wind and the building structure, currents and long-period ocean wave also affects microtremor vibration (Motamed, et al, 2007). While according to (Lang and Schwarz, 2004), microtremor is a short-period noise that comes from artificial sources.

The source of microtremor wave comes from all direction and then they resonate with each other. The microtremor wave according to (Bonnefoy-Claudet, et al, 2006b) consists of love and Rayleigh waves. According to Mirzaoglu and Dykmen (2003), the presentation of microtremor wave can be seen in Figure 1, where the microtremor signal consists of vertical component, which is *Up-Down* (UD) and two horizontal components, which are *East-West* (EW) and *North-South* (NS). The range of microtremor period is 0.05 to 2 seconds (Ibrahim & Subarjo, 2005). According to Mirzaoglu and Dykmen (2003), microtremor based on the range period is divided into two, which are short-period microtremor and long-period microtremor. The short-period microtremor has period that is less than 1 second. This period only shows shallow subsurface structures. While, the long-period microtremor has period that is more than 1 second and it relates to the deeper structure to the base of hard rock.

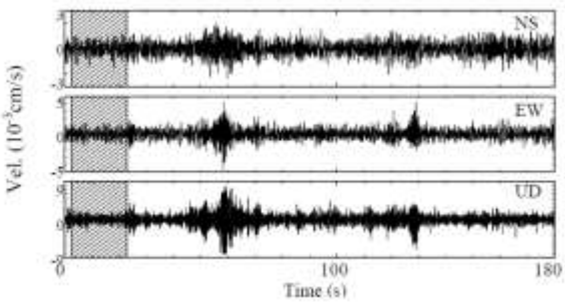

Figure.1 Presentation of microtremor in the software (Mirzaoglu and Dykmen, 2003)

Rayleigh Wave Ellipticity

Ellipticity from Rayleigh wave is defined as a ratio between horizontal and vertical component signal amplitude (H/V). Rayleigh wave ellipticity can be measured using single seismic station (Hobinger, 2011). Hobinger (2011) modeled H/V curve from the signal at the center of noise distribution seismic sensor circuit to estimate the accuracy of H/V curve on Rayleigh wave ellipticity. Estimation of ellipticity on single sensor with a case of Love wave results in H/V curve that is over-estimated on all of frequency range, except for the peak range, yet it is still acceptable. While H/V curve model that has Love wave also experiences a strong overestimation on all frequency range.

Ellipticity curve can be used to obtain parameter of share wave velocity of the surface (vs) at the review point through inversion process. The completion of the inversion process depends on the ability to determine parameter price that is close to observation data price by performing iteration. The accuracy of this process can be seen from the misfit value. The lower the misfit value from the iteration process, the better the profile of share wave velocity will be (Patimah, 2017).

Horizontal Vertical Time Frequency Analysis (HVTFA) Method

Horizontal Vertical Time Frequency Analysis (HVTFA) Method aims to minimize the effect of love wave on the ellipticity curve. The basic of this method is the implementation of *Continuous Wavelet Transform* (CWT) (Poggi et al., 2012). It is different from the classic H/V method, the

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ratio measurement in HVTFA method does not involve all of spectrum of horizontal and vertical components from the microtremor data. In contrast, representation of horizontal and vertical components is measured using CWT. The equation for CWT can be seen on the equation.

$$CWT_{[x](a,b)}=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{\infty}\Psi^*\left(\frac{t-b}{a}\right).dt$$

Where, α = dilatation parameter; β = translation parameter; t= time; and Ψ= wavelet function.

Wavelet function used in HVTFA method is Morlet wavelet that has been modified in the frequency domain centered on the frequency of f_c, as showed in the equation.

$$\frac{1}{\sqrt[4]{\pi}}\exp\left(-\left(\frac{f}{f_c}\omega_0-\omega_0\right)^2 m\right)$$
(2)

Where, f= frequency; ω_o= first Morlet parameter; m = second Morlet parameter (Atashband and Esfahanized, 2012)

The selection of wavelet parameter becomes necessary. A small value of (<6) provides a good result, but lack of resolution. In contrast, a too high value (>50) caused the separation of different wave contribution in the horizontal component cannot be entirely successful (Poggi et al, 2012).

3. RESEARCH METHOD

This research was performed using data from the point of mecrotremor measurement that has an amount of 1, which is in the coordinate of 112.63515 East Longitude and 7.70540 North Latitude. This research used 8 microtremor data that came from one measurement point with different measurement duration, which were 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, and 7 hours. Each data was processed using HVSR and HVTFA methods in *Geopsy* software. And then, the inversion of ellipticity curve was performed in *dinver* software to obtain vs30.

For HVTFA processing, the microtremor data that had been in .msd format were processed in *Geopsy* software. The selection of wavelet parameter m for HVTFA processing became necessary. A small value of (<6) provided a good result, but lack of resolution. In contrast, a too high value (>50) caused the separation of different wave contribution in the horizontal component cannot be entirely successful (Poggi et al, 2012). In addition to wavelet parameter, the frequency was also determined. In this research, the frequency used was 0.5 – 15 Hz and the value of wavelet parameter used was 10. Those values were the default values from *Geopsy* software. After performing HVTFA processing, it produced data with .max format. The data must be converted into .hv format, so it can be processed in the *dinver* software. The conversion of the .hv format was performed using *Max2curve* software.

The first step to process the data using HSVR was windowing microtremor data. The windowing process was performed on the three components of microtremor data, which were two horizontal components (N-S and E-W) and one vertical component (U-D). The length of window used in this research was 25 seconds with the frequency range of 0.5 to 15.00 Hz. It was necessary to use anti-triger algorithm based on the equation of STA (Short Term Average)/ LTA (Long Term Average), so that the transient signals often recorded during the measurement did not enter the window while performing windowing. After using anti-triger algorithm, signals entering the window were only tremor signals used in HVSR analysis. For other parameter determined, which was smoothing used Konno and Ohmachi smoothing filter with a constant of 40. After all of parameter had been set, HVSR process could be run to obtain H/V curve. Next, the H/V curve was saved in .hv format.

In this research, data of processing result was share wave velocity vs30 model and ellipticity curve of each data from the processing using HVSR and HVTFA methods with measurement duration of 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours, 6 hours, and 7 hours. The error value of each velocity model was calculated using error equation vs%Miss and Boun%Miss introduced by (Atashband and Esfahanizadeh, 2012). vs%Miss was error of velocity value on each layer of the velocity model. Boun%Miss was error from the depth of the first layer of the velocity model. The equation of vs%Miss and Boun%Miss can be seen in the equation (3) and (4)

$$vs\%Miss = \frac{Vs_{source} - Vs_i}{Vs_{source}} \times 100$$

(3)

$$Bound\%Miss = \frac{H_{source} - H_i}{H_{source}} \times 100$$

(4)

Where, Vs_{source} was the source of share wave velocity with a more reliable condition. According to (Atashband & Esfahanizadeh, 2012), the velocity model from the microtremor data with duration of 7 hours was a more reliable model. Vs_i was other share wave velocity that was going to be compared to Vs_{source}. vs%Miss can be calculated for each depth from the ground velocity model. While for equation (4), H_{source} was the thickness of the first layer of the ground velocity model from microtremor data with duration of 7 hours, and H_i was the thickness of the first layer of the ground velocity model that was going to compared to H_{source}.

In addition to vs%Miss and Boun%Miss, another error value equation was also used in this research. The equation was Ev and Eb equation introduced by (Davoodi, et al., 2008). The value of Ev and Eb used in this research was the value of Ev30 and Eb30. The Ev30 was the error value of the velocity from the vs30 model. The Eb30 was the number of depth error of each ground surface from the vs30 model. The equation of Ev30 and Eb30 can be seen in the equation of (5) and (6).

$$Ev30 = \frac{\sum\left(\frac{Vs_{source} - Vs_i}{Vs_{source}} \times 100 \times H_i\right)}{\sum H_i}, \quad \left(\sum H_i = 30\ m\right)$$

(5)

$$Eb30 = \sum \left| \frac{H_{source} - H_i}{H_{source}} \times 100 \right|$$

(6)

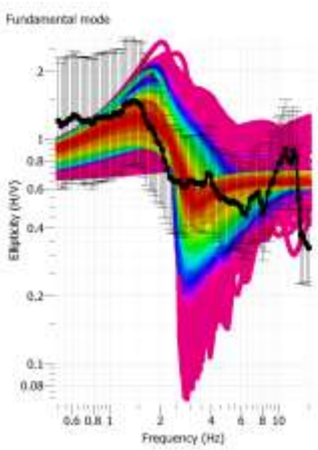
Where Vs_{source} was the source of share was wave velocity and Vs_i was other share wave velocity that was going to be compared to the source of share wave velocity. The value of the source of share wave velocity obtained from the share wave velocity model from the data with duration of 7 hours having a reliable model according to Atashband and Esfahanizadeh (2012). While for the equation of Eb30, H_{source} was the source depth and H_i was the depth of velocity model that was going to be compared to the source. The error calculation obtained was then presented in graphic, so it can be analyzed easier.

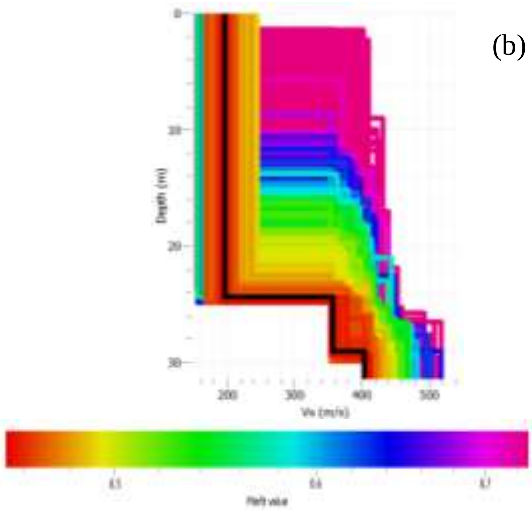
4. FINDING AND DISCUSSION

The Inversion Result of Ellipticity Curve

The inversion of ellipticity curve performed in the *dinver* program produced two outputs, which were ground profile moded to a depth of 30 meter and ellipticity curve resulted from the inversion. The two outputs were also accompanied with *misfit* showing the error value from the result of inversion. The inversion result of ellipticity curve for HVTFA method using data of 7 hours can be seen in Figure 2 and HVSR method using data of 7 hours can be seen in Figure 3.

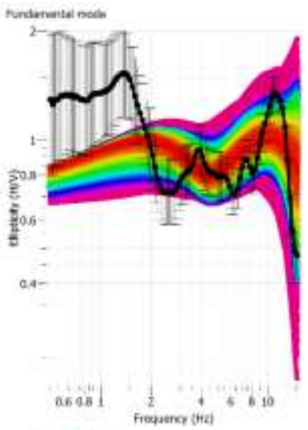
(a)



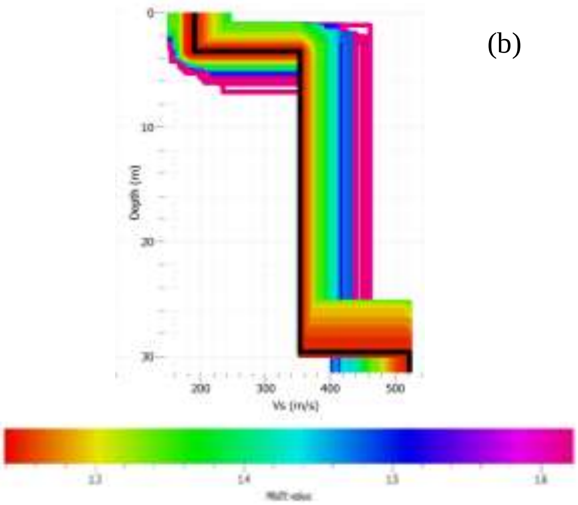


(b)

Figure.2 (a) ellipticity curve and (b) share wave velocity model from microtremor data with duration of 7 hours using HVTFA method



(a)



(b)

Figure.3 (a) Ellipticity curve and (b) share wave velocity model from microtremor data with duration of 7 hours using HVSR method

Based on Figure 1 and 2, microtremor data with duration of 7 hours resulted in different inversion outputs. It can be seen from Figure 1 and Figure 2 that the *misfit* value from the two figures had different value where the *misfit* value from the output of HVTFA method inversion was lower than HVSR method. The lowest *misfit* value from HVTFA method was around 0.45, while the lowest *misfit* value from HVSR method was 1.24. According to PAimah (2017), the lower *misfit* value from the iteration process, the better the share wave velocity profile obtained. In the research performed by Hobinger (2011), the *misfit* value considered as the best velocity model had value of (0 ≤ *misfit* < 1). In the velocity model in HVSR method (Figure 2), the *misfit* value reached 1.24. If it was seen from the ellipticity curve from the two models, the ellipticity curve in HVTFA method (Figure 1) had the velocity model with the lowest *misfit* value shown by red and it almost approached the ellipticity curve (the black line). It was because there were many of love wave found in the ellipticity curve in HVSR method. In contrast, in the ellipticiy curve in HVTFA methods, the love wave could be minimized using *Continuous Wavelet Transform* (CWT) where Morlet wavelet had been modified so it can select the wave based on the shape of the wave. By CWT, the love wave can be minimized and the Rayleigh wave can be kept because it was used for the inversion of ellipticity curve.

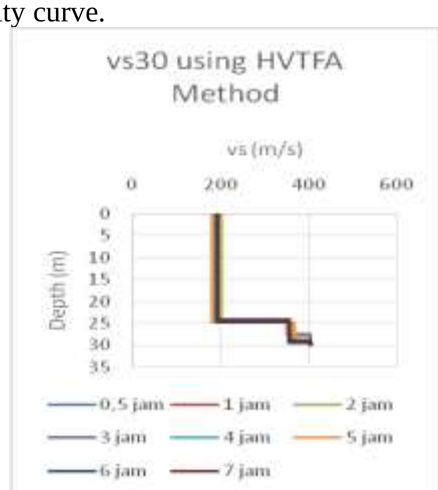


Figure.4 Share wave velocity model with HVTFA method

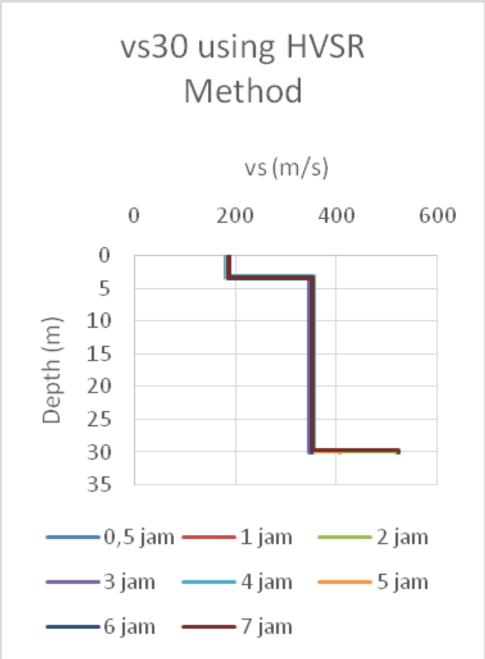


Figure.5 Share wave velocity model with HVSR method

The velocity value as the output result of HVSR method also had difference. The velocity model from HVTFA and HVSR method for each measurement duration can be seen in (Figure 4) and (Figure 5). The vs30 value obtained from the velocity model with HVTFA and HVSR method was significantly different. The vs30 value from the velocity model with HVTFA method had smaller range of value than HVSR method, which were 404.75 m/s to 406 m/s, while the range of vs30 value of HVSR method were 351.11 m/s to 522.89 m/s. The velocity model with HVSR method also had model that only had 2 ground layers, it was found in the data with duration of 1 hour, 3 hours, and 6 hours. The high range of vs30 value and the different number of layer proved that the ellipticity curve with HVSR method also had a big over-estimation.

Analysis of vs%Miss and Boun%Miss Value

The error value of vs%Miss was the error value for the share wave velocity in each depth, while Boun%Miss was the error value for the first layer depth in the velocity model. The calculation result of vs%Miss value from HVTFA method was shown by Figure 6, while vs%Miss was shoen by Figure 7. Based on both of figures, the vs%Miss value from HVSR was higher than vs%Miss from HVTFA method. The minus (-) value found in vs%Miss showed that the vs value was less than the vs source. The vs%Miss value from HVTFA method was (-3.85≤vs%Miss ≤6.95). The vs%Miss value from HVSR method was (-28.75≤vs%Miss≤14.59). The Boun%Miss value from HVTFA and HVSR method can be seen in Figure 8.

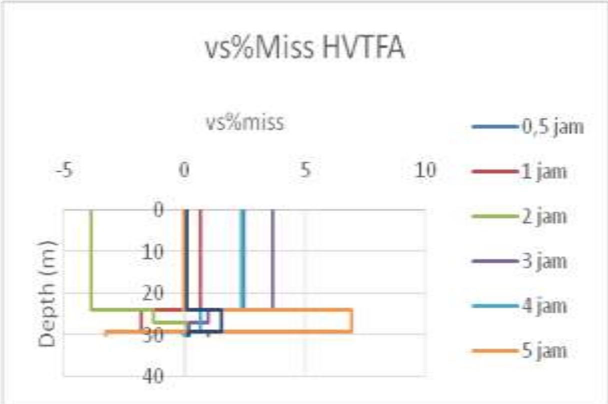


Figure.6 vs%Miss HVTFA

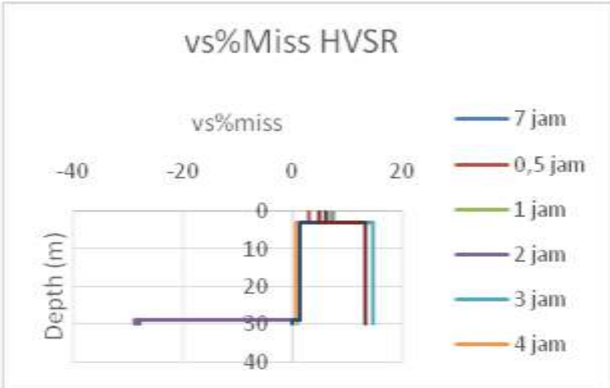


Figure.7 vs%Miss HVSR

The Boun%Miss value shown in Figure 8 showed a significant gap between the Boun%Miss value of HVTFA and HVSR method. The Boun%Miss value of HVTFA was only from 2.02 to 2.84 and the Boun%Miss value of HVSR reached 85.29 to 86.94.

Based on the vs%Miss and Boun%Miss value from HVTFA and HVSR method, it can be found that vs30 model from HVTFA method was more reliable than HVSR method. It was because the vs%Miss and Boun%Miss value from HVTFA method was categorized as reliable, it was based on Atashband and Esfahanizadeh (2012) stating that a reliable velocity model had vs%Miss and Boun%Miss value of (-20<vs%Miss<20) and (Boun%Miss<20). Therefore, the vs30

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model from all data, which were 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours were categorized as reliable vs30 model. In vs%Miss with HVSR method, there was an error value that was not categorized as reliable model, which was in the data of 0,5 hour, 2 hours, and 7 hours. The error value for those data were (-28,75 ≤vs%Miss≤6,70). While for vs%Miss value from other data were (0≤vs%Miss≤14.59). Meanwhile, the Boun%Miss value of HVSR method was 85.29 to 86.94, so it did not meet the requirement for a reliable model. In HVSR method, there was data having vs%miss value meeting the requirement for a reliable model. However, to be a reliable model, it required vs%Miss and Boun%Miss value meeting the requirement of reliable mode. Therefore, based on the vs%Miss and Boun%Miss Value, the vs30 model with HVSR method was not reliable, while the vs30 model with HVTFA method was reliable.

Figure.8 Boun%Miss of HVTFA and HVSR Method

Analysis of Ev and Eb Value

The Ev and Eb value was the calculation of error value that was similar to vs%Miss and Boun%Miss, where Ev30 was the error value of velocity from vs30 model. Eb30 was the number of depth error of each ground level from the vs30 model. The Ev30 and Eb30 value was presented in Figure 9 and

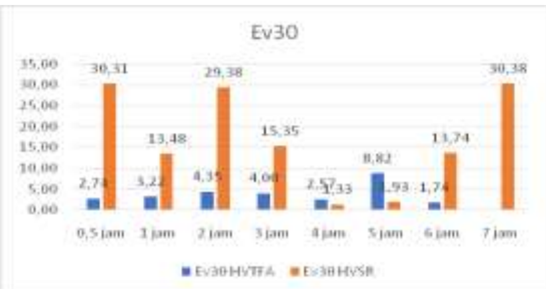

Figure 10

Table.1 The velocity value from the velocity model with HVTFA and HVSR with the lowest misfit *value*

Duration (hour)	HVTFA		HVSR	
	Depth (m)	vs (m/s)	Depth (m)	vs (m/s)
0.5	0 – 24.86	189.35	0 – 3.17	181.11
	24.86 – 29.52	353.58	3.17 – 29.62	351.11
	29.52 - 30	404.24	29.62 - 30	519.34
1	0 – 24.86	192.84	0 – 3.27	181.11
	24.86 – 29.62	362.31	3.27 - 30	352.88
	29.62 – 30	400.75		
2	0 – 24.86	201.58	0 – 3.27	181.11
	24.86 – 27.44	360.55	3.27 – 29.72	352.88
	27.44 – 30	404.24	29.72 - 30	517.5
3	0 – 24.76	187.01	0 – 3.37	179.48
	24.76 – 27.93	352.48	3.37 30	345.68
	27.93 – 30	404		
4	0 – 24.76	189.48	0 – 3.2	181.11
	24.76 – 29.22	353.58	3.2 – 29.72	353.58
	29.22 – 30	404.75	29.72 - 30	404.75
5	0 – 24.96	180.61	0 – 3.47	182.43
	24.96 – 29.02	367.55	3.47 – 29.72	351.11
	29.02 – 30	404.24	29.72 - 30	404.75
6	0 – 24.86	191.1	0 – 3.57	184.65
	24.86 – 29.62	355.32	3.57 - 30	351.11

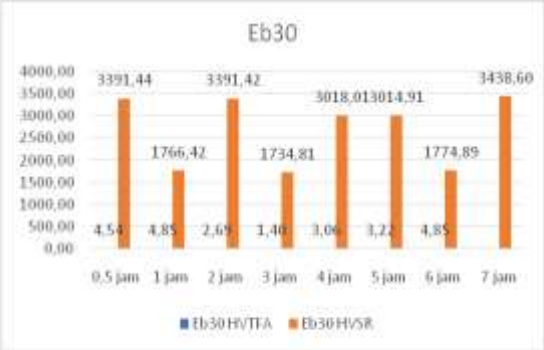

Figure.10 The Eb30 value with HVTFA and HVSR Method

Figure 9 showed the Ev30 value, the Ev30 value with HVTDA method was 1.4 to 8.82 and the Ev value of HVSR was 1.33 to 30.30. The Ev30 value with HVSR method was unique, it had The Ev30 value that was lower than HVTFA method, which was shown in data 4 hours and 5 hours. The Ev30 value in the data of 4 hours and 5 hours were 1.33 and 1.93. if it was seen from the table 1 showing the share wave velocity value on each depth, the velocity data in HVSR method of 4 hours and 5 hours had a small difference compared to the velocity value in the HVTFA method and it had the same number of layer with HVTFA method. However, it it was seen from Eb30 value, HVSR method had higher value than the Eb30 value with HVTFA method, which was 1734.81 to 3391.44. The Eb value of HVTFA method was only around 1.40 to 4.85. According to Atashband and Esfahanizadeh (2012), a reliable vs30 model had Ev30 and Eb30 value that was less than 20. Based on the requirement, the vs30 model from HVTFA method was categorized as reliable model, while the vs30 model from HVSR method was not reliable because the Eb30 value was more than 20 even though the Ev30 value had data having Ev30 value that was less than 20.

5. CONCLUSSIONS

Based on the research performed, it can be concluded as follows:

1. HVTFA method was more reliable than HVSR method for vs30 model. It was shown by the overestimation found in the ellipticity curve resulted from the inversion of HVSR method that was higher than HVTFA method. The *misfit* value from HVTFA method met the requirement of the best velocity model according to Hobinger, 2011 having the value of 0.44 to 0.45. While the *misfit* value from HVSR method was 1.2 to 1.3 in which the value did not meet the requirement of the best velocity model because the value was more than 1. The calculation result of error value of vs%Miss, Boun%Miss, Ev30, and Eb30 from the vs30 model with HVTFA method met the requirement of reliable model according to Atashband and Esfahanizadeh (2012), while HVSR method did not met the requirement.
2. The share wave velocity model to a depth of 30 meter (vs30) from the microtremor data of 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours, 5 hours and 6 hours using HVTFA method had reliable model. It was proven by the error value of vs%Miss and Boun%Miss, which was (-5<vs%Miss<10) and (2,02≤ Boun%Miss≤2,84), the Ev30 and Eb30 value, which was (1,4≤ Ev30 ≤8,82) and (1,40≤ Eb30 ≤4,85) that was considered to have the error value meeting the requirement of the reliable model according to Atashband and Esfahanizadeh (2012).

6. REFERENCES

Atashband, S., & Esfahanizadeh, M. (2012). Effects Evaluation of Ambient Vibration Recording Conditions on HVTFA Results. LISBOA: 15 WCEE.

Bonnefoy-Claudet, S., Cornou, C., & Bard, P. (2006b). The nature of noise wavefield and its applications for site effects studies. *Earth-Science Reviews* (doi:10.1016/j.earscirev.2006.07.004) .

Davoodi, M., Haghshenas, Esfahanizadeh, Mirjalili, M., & Atashband, S. (2008). Evaluating the Reliability of f-k and SPAC methods. *The 14 World Conference on Earthquake Engineering, 02-0161*, 9.

Hobinger, M. (2011). *Polarization of Surface Waves : Characterization, Inversion and Application to Seismic Hazard Assessment.* Saint-Martin-d'Heres: Universite de Grenoble.

Ibrahim, G., & Subarjo. (2005). *Pengetahuan Seismologi.* Jakarta: Badan Meteorologi dan Geofisika.

Kanli, A., Tildy, P., Prónay, Z., Pinar, A., & Hermann, L. (2006). Vs 30 Mapping and Soil Calssification for Seismic Site Effect Evaluation in Dinar Region, SW Turkey. *Geophysics Journal International, 165*, 233-235.

Knapmeyer-Endrun, B., Golombek, M. P., & Ohrnberger, M. (2017). Rayleigh Wave Ellipticity Modeling and Inversion for Shallow Structure at the Proposed InSight Landing. *Space Sci Rev, 211*, 339– 382.

Lang, D., & Schwarz, J. (2004). Instrumental Subsoil Clasification of Californian Strong Ground Motion Site Based on Single Measurments. *1*, 66. Lay, T., & Wallace, T. C. (1995). *Modern Global Seismology.* San Diego: Academic Press.

Lilie, R. J. (1999). *Whole Earth Geophysics.* New Jersey: Prentice-Hall.

Mirzaoglu, M., & Dykmen, U. (2003). Application of Microtremor to Seismic Microzoning Procedure. *Journal of The Balkan Geophysical Society, 6*, 3.

Motamed, R., Ghalandarzadeh, A., Tawhata, I., & Tabatabei, S. (2007). Seismic Microzonation and Damage Assessment of Bam City, Southern Iran. *Journal of The Balkan Geophysical Society, 11*, 110-132.

Mussett, A. E., & Khan, M. A. (2000). *Looking Into the Earth.* New York: Cambridge University Press.

Nandi. (2006). *Gempa Bumi.* Bandung: UPI.

Patimah, S. (2017). *Analisis Litologi Bawah Permukaan Berdasarkan Ground Profiles Kecepatan Gelombang Geser dengan Metode Ellipticity Curve di Kecamatan Prambanan dan Kecamatan Gantiwarno Kabupaten Klaten.* Yogyakarta: Universitas Negeri Yogyakarta.

Poggi, V., Fah, D., Burjanek, J., & Giardini, D. (2012). The Use of Rayleigh-wave Ellipticity for Site-Specific Hazard Assessment and Microzonation: Application to The City of Lucerne, Switzerland. *Geophysical Journal International, 188*, 1154-1172.

Telford, W. M., Geldart, L. P., & Sheriff, R. E. (1990). *Applied Geophysics.* Cambridge: Press Syndicate of the University of Cambridge.

UU no 24. (2007). Undang - Undang Republik Indonesia Nomor 24 Tahun 2007.