Combination of Passive Seismic (HVSR) and Active Seismic (MASW) Methods to Obtain Shear Wave Velocity Model of Subsurface in Majalengka

A P Budi1,*, R A Ginting1, B Sunardi2, and I N Sukanta3

1 Program Studi Geofisika, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika
2 Pusat Penelitian dan Pengembangan, Badan Meteorologi Klimatologi dan Geofisika
3 Sekolah Tinggi Meteorologi Klimatologi dan Geofisika

*Email: prasetiaachmad05@gmail.com

Abstract. Majalengka is a district in West Java which is located close to local faults and subduction zone, so that made this area has a high enough risk of earthquake hazards. Engineering Seismology Team of Meteorology Climatology and Geophysics Agency has been carried out microtremor and MASW survey in Majalengka. The combination of HVSR and MASW inversion methods is applied to obtain the value of the shear wave velocity (Vs), a combination of the two methods is expected to overcome the deficiency of each method. Results of the distribution of the value of the shear wave velocity can explain the subsurface conditions related to a vulnerability in the study area to seismic hazards. The results of HVSR and MASW inversion are 1-D (Vs) profiles at each measurement point, after that interpolated to obtain a 3-D Vs30 model. The results showed that Vs30 values in Majalengka District varied around 80 - 1500 m/s. Layers with low (Vs) values were relatively thick dominant in the north and northwest regions of the study area, soil types in this area were mostly composed of medium soils, a small part was composed of soft soil layers and rock layers. Therefore, in theory, the disaster in the north and northwest regions has a relatively higher vulnerability compared to other regions in Majalengka District.

1. Introduction
Majalengka is a district in West Java that is prone to earthquake shocks. This is due to the geographical location of Majalengka which monitors the activity of tectonic plate movements, namely the Indo-Australian plate subduction that penetrates the Eurasian plate and local faults around the area, namely the Cimandiri fault, Lembang fault, and Baribis fault [1]. In addition, in this area, there were at least two destructive earthquakes, namely the M 5.8 earthquake in 1990 and the M 5.3 earthquake in 2001 [2]. Judging from the geological conditions (Figure 1), the study area is dominated by young volcanic rocks (Qyu) and alluvial layers (Qa) that cover the layers underneath inconsistently. In terms of rock formations, the area is dominated by the Halang Formation (Mhl), the Kaliwungu Formation (Pk), and Quaternary Deposits. The Halang Formation consists of two members, namely the upper members which are composed of sandstones, tuffs, conglomerates, and clay stones. While the members below are composed of volcanic breccias that are andesite and basalt [3]. The lithology of the Kaliwungu formation that spreads north of the city of Majalengka to the Subang area is composed of claystone, marl, and green glauconite sandstone [4].
To minimize the impact of damage caused by an earthquake, the structural design of the building should pay attention to the vulnerability factor (vulnerability) or local conditions of the local soil in response to earthquake vibrations [6, 7]. This is because the soil sediment is thick enough to cause acceleration amplification and changes in the frequency content of ground vibrations [8]. One method that can be used to estimate the local conditions of the local soil is to perform a shear wave velocity (Vs) analysis.

To estimate subsurface conditions, various methods can be used, such as the HVSR (Horizontal to Vertical Spectral Ratio) or MASW (Multichannel Analysis Surface Wave) method. The difference between the two methods is the source of the recorded waves. The HVSR method developed by Nakamura (1989) utilizes a passive source or natural vibration to estimate the local dominant frequency of the local soil while the MASW method utilizes active sources (hammer blows, blast loads, etc.) to measure the velocity of dispersive Rayleigh surface wave propagation which is then carried out. Inversion analysis to determine the velocity profile of shear waves to depth [9, 10].

In the inversion process, generally, the model solution produces a non-uniqueness due to the presence of noise or (noise) in the observed data and the lack of limiting the model space in the inversion process [11]. Therefore, this study tries to apply a combination of passive (HVSR) and active (MASW) methods. The HVSR method generated from natural sources is a method that utilizes natural vibrations generated by the earth so that the dominant frequency generated can represent the thickness of the sediment or the depth of the bedrock at the measurement point [12]. With information about the depth of bedrock, it can be used as supporting information for designing building foundations. The MASW method generated from an active source (hammer blows) gives a high wave amplitude and a short wavelength. As a result, the penetration of the wave is only able to reach shallow depths but has a high sensitivity to differences in the density of the rocks it passes through [13]. Therefore, this combination technique is applied to reduce the uncertainty level of the model solution from one of the methods and it is expected that the results of this technique will obtain complex information about the Vs model below the surface.

2. Method
The data used in this study included 25 microtremor measurement data and 24 MASW points. The research location covers the Majalengka District area with a coordinate range of 6.775° S - 6.890° S and 108.175° - 108.290° E. The process of taking microtremor data was carried out using a LE-3Dlite
MkIII (Short-period Seismometer) seismometer with a duration of 45 minutes. Meanwhile, the MASW data collection process is carried out by providing an active vibration source (hammer blows) on a metal plate connected to 24 geophone sensors.

![Microtremor and MASW Measurement Coordinates in Majalengka District](image)

**Figure 2.** Microtremor and MASW Measurement Coordinates in Majalengka District

2.1. *Passive Seismic Method (HVSR)*

Signal data from microtremor measurements in miniSEED (*.SEED) format consists of three components, namely Z (vertical / Up-Down), N-S (North-South), and E-W (East-West). The data is processed using Geopsy Software to obtain an H/V curve display that shows the dominant frequency and amplification factor at the measurement point. When processing using Geopsy Software, the sampling frequency is 100 Hz, the frequency range is 0.5 - 15 Hz, and the length window is 25 s. To ensure the reliability and clarity of the HVSR peak, criteria are used in the guideline in SESAME (Site Effects Assessment using Ambient Excitations) [14].

![HVSR Processing Method](image)

**Figure 3.** HVSR Processing Method
To get the frequency value data against the amplitude of the H/V curve, you can do it in Geopsy Software by saving the curve in the format (*.hv) then changing the format into the format (*.txt) as data preparation or input for inversion. Then the inversion process was carried out using OpenHVSR software to obtain Vs 1-D profiles against depth [15]. Besides, the quality of signal can be seen in the Max2curve Package in Software Geopsy [16].

2.2. Active Seismic Method

MASW data processing is done using SeisImager Software. MASW measurement data in the form of time signal data (m/s) to depth (m) in the (*.SEGY) format is transformed into the frequency domain (Fast Fourier Transform), a Fourier transformation process with a frequency range of 0 - 40 Hz and a phase speed range of 0 - 2000 m/s at intervals of 0.5.

![Figure 4. MASW Processing Method](image)

After that, picking the fundamental mode is carried out on the phase velocity (m/s) curve against frequency (Hz). The fundamental mode is picked because, in its propagation the Rayleigh wave will ideally be measured in a single-mode called the fundamental mode. In addition, the vertical particles that can be detected only come from the propagation of R wave energy [17], so that only the fundamental mode works in wave analysis using passive sources [18]. Then an inversion process is carried out to obtain a 1-D Vs profile for depth.

2.3. Vs30 Data Processing

In the inversion process, the initial model parameter values are needed to determine the theoretical shear wave velocity. The average velocity of shear waves is obtained by iterating between the theoretical shear wave velocity and the observed shear wave velocity until a small RMS (root mean square) error is obtained. However, if the error value is still large, it is necessary to iterate again until the smallest RMS value is obtained. The value of the average shear wave velocity at a depth of 30 meters can be calculated from the shear wave velocity profile. Mathematically it can be written:

\[
V_{s_i} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} \frac{d_i}{V_{s_i}}} \tag{1}
\]

Where \(d_i\) is the thickness of each layer \(i\) in meters, \(V_{s_i}\) is the shear wave velocity at layer \(i\) expressed in m/s, and \(\sum_{i=1}^{n} d_i\) is the observed subsurface depth [19]. To determine the value of Vs30, the depth of the subsurface under review is 30 meters. Then the above equation can be written as:

\[
V_{s30} = \frac{30}{\sum_{i=1}^{n} \frac{d_i}{V_{s_i}}} \tag{2}
\]

The value of shear wave velocity to a depth of 30 m (Vs30) is an important parameter in the study of local ground effects and the prediction of ground vibrations against earthquakes. Generally, the value of Vs30 dominates the amplification of ground motion due to earthquake shocks [20, 21].
2.4. Analysis of the Inversion Results by the HVSR and MASW Methods
The results of the inversion of the dispersion curve and the H/V curve in the form of a Vs profile against depth were analyzed based on the geological conditions of the local area and the Vs30 value according to the USGS (United States Geological Survey). If the results of the two methods at the same measurement coordinates are obtained the results of the Vs profile which are identical to the local geological conditions and the USGS Vs30 value, the results of the inversion of the entire HVSR and MASW data are carried out by an interpolation process to obtain the Vs30 model in the form of a 3-D model. After that, an analysis of soil types was carried out referring to SNI 1726: 2019 (Table 1), the depth of bedrock, and the vulnerability of the local area to earthquake hazards.

Table 1. Site Classification (SNI 1726: 2019)

| Site Classification | Vs (m/s)                  |
|---------------------|---------------------------|
| SA                  | s ≥ 1500                  |
| SB                  | 750 < s < 1500            |
| SC                  | 350 < s ≤ 750             |
| SD                  | 175 < s ≤ 350             |
| SE                  | s < 175                   |
| SF                  | Locations requiring specific geotechnical investigations and response analysis Each soil layer profile that has one or more characteristics such as vulnerable and potentially failing to earthquake loads such as clay soil liquefaction is very sensitive, high plasticity. |

3. Results and Discussion
This study uses a combination of passive seismic (HVSR) and active seismic (MASW) methods to determine soil vulnerability in the Majalengka area through analysis of the shear wave velocity values up to a depth of 30 m (Vs30), soil type, and bedrock depth in the study area.

3.1. The Result of Passive Seismic Method (HVSR)
After processing the microtremor measurement results at 25 measurement points, the dominant frequency data and the frequency to amplitude curve data are obtained. The HVSR curve was analyzed using the SESAME standard with various conditions that must be met so that processing can be considered reliable. Then the HVSR inversion was carried out at 25 measurement points in Majalengka District until the Vs 1-D profile was obtained for the depth for each measurement point. After the inversion process, 11 Vs 1-D profiles were obtained with relatively small RMS. So that these 11 profiles do the combination process.

An example of the inversion result is shown in the image below. Figure 5 (a) shows the comparison of the observation data represented by the black line and the inversion best model represented by the red line.
Figure 5. (a). Comparison of Observational Data and The Best Model of HVSR Inversion Results (b). Model Vs 1-D Point Measurement M62

In Figure 5 (b), the Vs value at the measurement point M62 to a depth of 1.75 m about 80 m/s, a depth of 1.75 - 11.75 m about 270 m/s, and a depth of 11.75 - 23.25 m about 614 m/s, and depth of (23.25 m - depth unknown) about 1500 m/s. Based on the 1-D profile, to a depth of 11.75 m, the soil layer below the m62 measurement point consists of soft soil and medium soil. The average Vs30 value from the 11 measurement points is presented in Table 2.

| HVSR Point | Vs30 (m/s) | Site Classification |
|------------|------------|---------------------|
| m13        | 488.02     | Hard Soil (SC)      |
| m14        | 183.21     | Medium Soil (SD)    |
| m15        | 406.4      | Hard Soil (SC)      |
| m16        | 407.64     | Hard Soil (SC)      |
| m17        | 514.65     | Hard Soil (SC)      |
| m21        | 1409       | Rock (SB)           |
| m27        | 512.14     | Hard Soil (SC)      |
| m37        | 152.5      | Soft Soil (SE)      |
| m54        | 167.06     | Soft Soil (SE)      |
| m56        | 792.94     | Batuan (SB)         |
| m62        | 424.75     | Hard Soil (SC)      |

3.2. The Result of Active Seismic Method (MASW)
The results of MASW data processing in this study obtained 24 1-D Vs30 profiles. An example of the results of the 1-D inversion is shown in Figure 6, where interpolation will be carried out to obtain the Vs30 3-D model. Based on the results of MASW data processing at 24 measurement points, the average shear wave velocity value at a depth of 0-30 m in Majalengka District varies from 228.59 - 590.45 m/s.
Based on the value of $V_s$ at the MASW22 measurement point at a depth of 0 - 3.75 m of 194.4 m/s, a depth of 3.75 - 10 m of 374.6 m/s, a depth of 10 - 18.75 m of 555 m/s, and a depth of 18.75 - 30 m at 550.2 m/s. The $V_{s30}$ average value of the 24 measurement points is presented in Table 3.

### Table 3. $V_{s30}$ Value and Classification of Soil Types of MASW Method Processing Results

| MASW     | Point  | $V_{s30}$ (m/s) | Site Classification | Point  | $V_{s30}$ (m/s) | Site Classification |
|----------|--------|-----------------|---------------------|--------|-----------------|---------------------|
| masw1    | 251.43 | Medium Soil (SD)| masw13              | 451.2  | Hard Soil (SC)  |
| masw2    | 487.54 | Hard Soil (SC)  | masw14              | 467.62 | Hard Soil (SC)  |
| masw3    | 441.41 | Hard Soil (SC)  | masw15              | 399.28 | Hard Soil (SC)  |
| masw4    | 510.87 | Hard Soil (SC)  | masw16              | 228.59 | Medium Soil (SD)|
| masw5    | 317.7  | Medium Soil (SD)| masw17              | 366.81 | Hard Soil (SC)  |
| masw6    | 586.53 | Hard Soil (SC)  | masw18              | 328.46 | Medium Soil (SD)|
| masw7    | 389.78 | Hard Soil (SC)  | masw19              | 385.42 | Hard Soil (SC)  |
| masw8    | 254.64 | Medium Soil (SD)| masw20              | 414.67 | Hard Soil (SC)  |
| masw9    | 528.42 | Hard Soil (SC)  | masw21              | 585.45 | Hard Soil (SC)  |
| masw10   | 545.91 | Hard Soil (SC)  | masw22              | 415.78 | Hard Soil (SC)  |
| masw11   | 357.51 | Hard Soil (SC)  | masw23              | 292.33 | Medium Soil (SD)|
| masw12   | 312.62 | Medium Soil (SD)| masw24              | 386.43 | Medium Soil (SD)|

#### 3.3. Results of Combined MASW and HVSR Methods

The combination of MASW and HVSR methods is applied in this study with the aim of reducing the mismatch associated with the inversion of one of the methods, that is, generally, each inversion process contains ambiguity in interpretation so that the combination of these two methods is expected to overcome the shortcomings of each method.

Based on the results of MASW and microtremor data processing, there were 24 vs 1-D MASW measurements and 11 vs 1-D microtremor measurements (reliable) with consideration of the relatively small RMS value after the inversion process. Then the data is interpolated so that the $V_{s30}$ 3-D combination model is obtained. Before the data were interpolated, comparisons were made on several MASW and microtremor data with the same measurement coordinates to ensure that the results of the two methods were not significantly different even though each method had a relatively small RMS.
Figure 7 shows the comparison of the 1-D Vs Profile between the two methods at the same measuring point. Based on this figure, the results are not much different at a shallow depth.

![Figure 7. Comparison of Profiles Vs 1-D Measurement Points of MASW5 and M5](image)

Based on Figure 7, at a depth of 0 - 5 m the Vs value is around 190 m/s, the depth of 5 - 15 m the Vs value is around 316 m/s, and the depth of 15 - 30 m the Vs value is around 411 m/s for the MASW method, while in the method HVSR at a depth of 0 - 2 m the value of Vs is around 80 m/s, a depth of 2 - 10 m the value of Vs is about 211 m/s, and a depth of 10 - 21 m the value of Vs is about 571 m/s. Thus, overall the results of the Vs 1D profile from each method have not many different results for near-surface, but there are already significant differences as the depth increases. This is due to the characteristics of the active wave (Rayleigh wave) which is not sensitive to deeper depths [22]. The combined results of 11 HVSR inversion measurement points and 24 MASW measurement points in the Majalengka District are displayed in the form of a 3-D model of shear wave velocity (Vs) shown in Figures 8 – 9.

![Figure 8. Vs30 3-D Model Combination of HVSR and MASW Methods in Majalengka District](image)
Based on the 3-D model combination of MASW and HVSR methods. In general, the value of Vs in the Majalengka District varies around 80 - 1500 m/s. Layers with low Vs values (80 - 350 m/s) represented by blue to light blue colors are relatively thick, dominant in the north and northwest sides of the study area. Meanwhile, the depth of bedrock represented by green is relatively shallow towards the south and southeast of the research area which includes the villages of Babakan Jawa, Lebaksiuh, and Cibodas.

The average Vs30 value in Majalengka sub-district varies from 152.5 - 1409 m/s. Based on the results of processing, in terms of soil type and referring to the SNI 1726: 2019 site classification table, this area is composed of soft soil layers to rock layers. In general, the northern and northwestern areas of the study area which include Jatipamor, Cikasarung, Cijati, Tarikolot, and Majalengka Kulon villages are composed of soft soil layers. Meanwhile, in the middle to the south, the research area is dominated by hard soil layers and partly composed of rock layers.

![Figure 9](image_url) (a). Model Vs30 3-D Layer 1, (b). Layer 2, (c). Layer 3

**Figure 9.** (a). Model Vs30 3-D Layer 1, (b). Layer 2, (c). Layer 3

Figure 10. Map of USGS Vs30, Majalengka District
The results shown are in accordance with the geological conditions of the study area wherein the northern area of the study area is dominated by alluvials and coastal sediments. In addition, this fact also corresponds to the USGS Vs30 map where the northern region of the study area has a lower Vs value compared to the southern region of the study area. Thus, in disaster theory, the northern and northwestern disaster areas of the Majelengka District have a relatively higher potential for damage if an earthquake occurs compared to other areas. These areas include Batipamor, Cikasarung, Cijati, Tarikolot, and Majalengka Kulon Villages, which are areas with low shear wave velocity values and relatively deep bedrock depth compared to other areas. Therefore, this area deserves special attention in efforts to mitigate the danger of earthquakes considering that in this area there have been destructive earthquakes.

4. Conclusions
Based on the 3-D model combination of the HVSR and MASW methods, the average Vs30 value in Majalengka sub-district varies from 152.5 - 1409 m/s. The classification of soil types in the Majalengka District based on the value of Vs30 varies from soft soil (SE) to rock (SB). In general, the northern and northwestern areas of the study area are composed of soft and medium soils. Meanwhile, in the middle to the south, the research area is dominated by hard soil layers and partly composed of rock layers. Generally, areas with deep bedrock depth are found in the north and northwest areas of the study area. Then the relative sediment thickness is getting thinner towards the south to the southeast of the study area.

The results of the imaging of the subsurface model using the combination method were obtained only to a depth of 30 m. Based on this model, the northern and northwestern regions have relatively higher vulnerabilities compared to other areas in Majalengka District. This is because the area has a deep bedrock depth and is dominated by soft to medium soils. Thus, referring to the type of soil and the depth of the bedrock, the district of Majalengka needs special attention in efforts to mitigate the danger of earthquakes considering that in this area there have been destructive earthquakes.

References
[1] Supartoyo, Putranto E T, and Djadja 2005 Active Faults and Destructive Earthquake Epicenter Distribution Map of Indonesia (Bandung: Direktorat Vulkanologi dan Mitigasi Bencana Geologi, Badan Geologi, Kementerian Energi dan Sumber Daya Mineral).
[2] Badan Meteorologi Klimatologi dan Geofisika 2019 Katalog Gempa Bumi Signifikan dan Merusak 1821-2018 (Jakarta: Pusat Gempa Bumi dan Tsunami BMKG).
[3] Bemmelen R W 1949 The Geology of Indonesia Vol. I A (Netherlands: The Haque).
[4] Silitonga and Djuri 1973 Geologi Lembar Arjawinangun (Bandung: P3G Bandung).
[5] Djuri 1973 Peta Geologi Lembar Arjawinangun Skala 1:100.000 (Bandung: Geologi Survey Indonesia).
[6] Martorana R, Capizzi P, Avellone G, Siragusa R, D’Alessandro A, and Luzio D 2014 Conf. Proc. Near Surf. Geosci. 2014 - 20th Eur. Meet. Environ. Eng. Geophys. Vol 2014 (Netherlands: The European Association of Geoscientists and Engineers (EAGE)) p 1.
[7] Sunardi B, Daryono, Arifin J, Susilanto P, Ngadmanto D, Nurdiyanto B, and Shahzad S 2012 J. Meteorol. Geofis. 13 131.
[8] Pawirodikromo W 2012 Seismologi Teknik dan Rekayasa Kegempaan (Yogyakarta: Pustaka Pelajar).
[9] Park C B, Miller R D, and Miura H 2002 Proc. Soc. Explor. Geophys. Jpn. 2002 vol 22 (Tokyo: Society of Exploration Geophysicists) p 23.
[10] Kanli A I, Tildy P, Próñay Z, Pinar A, and Hermann L 2006 Geophys. J. Int. 165 223.
[11] Grandis H 2009 Pengantar Pemodelan Inversi Geofisika (Jakarta: HAGI).
[12] Sutrisno W T 2014 Profiling Persebaran Kecepatan Gelombang Geser (Vs) Menggunakan Inversi Mikrotremor Spectrum Horizontal –to Vertical Spectral Ratio (HVSR) (Surabaya: Institut Teknologi Sepuluh Nopember).
[13] Park C B, Miller R D, Xia J, and Ivanov J 2007 Lead. Edge 26 60
[14] Site Effects Assessment using Ambient Excitations (SESAME) 2004 Guidelines for The Implementation of The H/V Spectral Ratio Technique on Ambient Vibrations (Eropa: European Commission – Research General Directorate).
[15] Bignardi S, Mantovani A, and Zeid N A 2016 Comput. Geosci. 93 103.
[16] Arimuko A, Santoso E, and Sunardi B 2020 J. Phys.: Conf. Ser. 1491 012031.
[17] Tokimatsu K 1997 Earthq. Geotech. Eng. 1333.
[18] Xia J, Miller R D, and Park C B 1999 Geophys. 64 691.
[19] Kanli A I, Tildy P, Prónay Z, Pinar A, and Hermann L 2006 Geophys. J. Int. 165 223.
[20] Lee C T and Tsai B R 2008 Terr. Atmos. Ocean. Sci. 19 671.
[21] Kanli A I 2011 4th IASPEI/IAEE Int. Symp. (California: University of California Santa Barbara) p 1.
[22] Castellaro S and Mulargia F 2009 Bull. Seismol. Soc. Am. 99 761.