Estimation of Shear Wave Velocity Using Horizontal to Vertical Spectrum Ratio (HVSR) Inversion to Identify Faults in Pacitan

A Haryono1,*, Sungkono1, M A Caesardi1, B J Santosa1, F Syaifuddin3 and A Widodo3

1 Department of Physics, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo Surabaya, 60111, Indonesia
2 Department of Physics, Universitas Mulawarman, Kampus Gunung Kelua Samarinda, 75123, Indonesia
3 Department of Geophysical Engineering, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo Surabaya, 60111, Indonesia

* Corresponding author’s email: arif.haryono@fmipa.unmul.ac.id

Abstract. Pacitan is one of the cities in Indonesia which is located around a subduction zone with many faults. Grindulu Fault is one of the active faults in Pacitan. In order to mitigate hazard in the area, detailed information about the existence and characteristic of the fault is needed. Thus, imaging of Grindulu Fault using shear wave velocity (Vs) was carried out. 1-D of Vs was revealed by inversion of HVSR from microtremor data using the Monte Carlo algorithm. Furthermore, several Vs were processed using interpolation approach to determine two-dimensional (2-D) cross-section of Vs. Based on the contrast of Vs and considering the geological conditions in Pacitan area, the existence of Grindulu Fault and other faults were identified.

Keywords: Shear wave velocity, HVSR inversion, Grindulu Fault

1. Introduction

Damage of a building due to an earthquake waves propagation through an area depends on local site effects (soil properties) and building conditions [1]. Therefore, research on subsurface soil properties is very important to minimize the impact of an earthquake (damaging houses or buildings). One method that is widely used to study the characteristics of subsurface soil is microtremor. Microtremor can identify how much effect caused by earthquake waves propagation in a site without requiring other geological information [2]. Microtremor is a method that is quite popular and widely used for site effect studies because the method is able to represent the level of amplification of ground motion and natural frequency of the site. One method that can be used to analyze microtremor data is the HVSR (Horizontal to Vertical Spectrum Ratio) method.

Researchers have different opinions about the waves that compose the HVSR curve. Bonnefoy-Claudet et al. [3] argue that H/V ratio is mainly controlled by local surface sources and mainly due to the ellipticity of the fundamental Rayleigh waves. So do Lachet and Bard [4] and Konno and Ohmachi [5] who claimed that microtremor was mostly composed of Rayleigh wave. Meanwhile, Nakamura [2] shows that the peak of the HVSR of microtremor cannot be explained by the energy of Rayleigh wave.
but can be explained by vertical incident SH wave. This is supported by Herak [6] which uses the HVSR curve inversion, namely the body wave-based inversion process, to determine the value of the shear wave velocity (Vs). Whereas Garcia-Jerez et al. [7] combine body waves and surface waves (SH, SV, Rayleigh, and Love) in an algorithm for HVSR data inversion to reveal Vs of subsurface.

Vs is one of the important parameters in finding soil models, especially in the sediment layer above the bedrock. The values of Vs can be generated through the inversion process of the HVSR curve [6,8]. The average shear-wave velocity for the topmost 30 m of sediments (Vs30) was also determined by Rošer and Gosar [9] using the joint modeling of three-component, microtremor, HVSR data and dispersion curves obtained through microtremor array measurements analyzed by the Extended Spatial Autocorrelation (ESAC) and Refraction Microtremor (ReMi) methods. In the measurement and data analysis processes, using HVSR curve inversion to determine Vs of subsurface has several advantages, including the relatively inexpensive survey costs and relatively fast data processing time. Thus, in this paper used OpenHVSR [8] to invert HVSR curve for deriving Vs of subsurface.

2. Geological setting

Pacitan is located in the eastern South Mountain Zone, which is dominated by karst and volcanic rocks. The eastern South Mountain Zone is divided into three sub-zones, namely the Baturagung, Wonosari, and Gunung Sewu Sub-zones. Baturagung Sub-zone is located in the northern part, extends from the west (Mount Sudimoro) to the east (Mount Gajahmungkur). The Wonosari Sub-zone is a plateau located in the Wonosari area, with basic rock structure dominated by limestone. Whereas the Gunung Sewu Sub-zone is a hill with karst landscape, which is a landscape with limestone hills. This karst landscape extends from Parangtritis Beach in the west to Pacitan Bay in the east.

The Southern Mountain Zone is formed by subduction activity due to interactions between the Eurasian Plate and Indo-Australian Plate. This interaction also produces several faults in the Pacitan area including Punung, Pucak, Tegalombo, Kayuwayang, Melokolegi, Grindulu, Pucunglangan, Buyutan, Karangrejo, Pakis, and Dayakan Faults [10,11]. The activity of Grindulu fault had caused several earthquakes in Pacitan area. The Grindulu Fault passes through densely populated areas in five districts, namely: Bandar, Nawangan, Punung, Arjosari, and Donorojo Districts.

The geological condition of the Pacitan area includes several formations which are mostly dominated by volcanic rocks including Watupatok, Mandalika, Dayakan, Wuni, Jaten, Semilir, and Nampol Formations. Meanwhile, the Wonosari Formation is dominated by karst, and the Arjosari and Oyo Formation consist of volcanic rock and karst. Figure 1 shows the geological map of Pacitan area.

![Geological Map of Pacitan Area](image-url)
3. Methods and data

3.1. Microtremor analysis

Microtremor is a ground vibration with an amplitude of about 0.1–1 microns and a velocity of 0.001–0.01 cm/sec which can be detected by certain seismographs \[12\]. A microtremor device has three orthogonal sensor components (NS, EW, and vertical), and the average HVSR in each window can be determined by:

\[
HVSR = \sqrt{\frac{(F_{NS}^2 + F_{EW}^2)}{(2F_V^2)}}
\]  

where \(F_{NS}\), \(F_{EW}\) and \(F_V\) are the Fourier amplitude spectra in the NS, EW and vertical directions, respectively \[13\].

Microtremor method has been used to estimate the dynamic characteristics of surface layers since the early 1950s \[14\]. Until now, microtremor data have been widely used to estimate dynamic properties and the HVSR method is an adequate tool to study subsurface soil structure. In data processing, the HVSR method produces the dynamic characteristics of the soil, namely natural frequency and amplification. Both of these dynamic characteristics are related to local effects that affect the size of building damage caused by an earthquake. The natural frequency \(f_0\) is influenced by the value of shear wave velocity on the surface layer \(V_S\) and the thickness of the subsurface sediment \(h\) as expressed by the following equation:

\[
f_0 = \frac{V_S}{4h}
\]  

while the amplification factor \(A\) for this frequency is related with impedance ratio. If densities for basement and surface layer are same then:

\[
A_0 = \frac{V_b}{V_S}
\]

where \(V_b\) denotes shear wave velocity of basement \[14\].

3.2. Inversion process

Inversion is a mathematical framework for transforming measurement data into model parameters. In the HVSR method, the inversion process can be used to determine the value of the shear wave velocity by minimizing the objective function namely the difference between observed and calculated HVSR data. Herak \[6\] published ModelHVSR, the inversion of the HVSR curve program, that is capable of obtaining the 1D distribution of the elastic properties of a subsurface. Further, Bignardi et al. \[8\] developed OpenHVSR to obtain the 2D and 3D subsurface models. Both of these programs use the Monte Carlo algorithm.

There are six parameters that represent the subsurface, including compression and shear wave velocity \(V_p, V_s\), thickness \(h\), density \(\rho\), and attenuation factors \(Q_p, Q_s\). The attenuation factors are frequency-dependent and follow:

\[
Q = Q_0 f^k
\]

where \(Q_0\) is the attenuation factor at 1 Hz and \(k\) indicates a constant which is assumed to be fixed for all sites \[8\].
3.3. Data

The tools used in this study are a set of microtremor, compass, accumulator, and computer for processing. Data acquisition was carried out directly at the location that was predicted of being passed by the Grindulu Fault and other faults. The measurement design consists of two lines, with the first and second lines each consisting of 13 points and 11 points (Figure 2). Furthermore, the microtremor data processes used the HVSR method and followed by the HVSR curve inversion process. In this study, the HVSR method used Geopsy software, while the inversion process used OpenHVSR software.

![Figure 2](image-url)  
**Figure 2.** The measurement design with two lines (red dots) that crossed the Grindulu Fault and other faults.

4. Results and discussion

Measured wave on the microtremor consists of three orthogonal components including the North-South (N), the East-West (E), and the vertical component (Z). In order to get HVSR curves from microtremor data, several steps were required. The first step is to carry out the filtering, windowing, and smoothing process on the recorded microtremor wave signal through Geopsy software. Based on the HVSR curve, the frequency and amplification values of each measurement point can be determined. Furthermore, the HVSR curves are used as input files in OpenHVSR software. The inversion process using OpenHVSR also requires model parameters ($V_p$, $V_s$, $\rho$, $h$, $Q_p$, $Q_s$) as initial values. Additionally, the algorithm also requires a number of iterations and a standard deviation of random normal for initializing model parameters in the Monte Carlo approach [6]. $V_s$ value was taken between 200–3200 m/s with the consideration that the Pacitan geological conditions are dominated by alluvium and the average $V_s$ value in the Southern Mountain Zone is in the 1800–3200 m/s range [15]. Consequently, initialization of $h$ and $V_s$ is set as in Table 1 which is revealed by Martha et al. [15]. $V_p$ (in km/s) is calculated based on the Castagna equation as described below [16]:

$$V_p = 1.16V_s + 1.36$$  
(5)

The density value is then calculated based on equation [17]:
Other model parameters, \( Q_s \) is determined based on geological conditions while \( Q_p \) is calculated using \( Q_p = 2Q_s \) [18]. The values of \( Q_s \) and \( Q_p \) do not significantly affect the resulting model.

\[
\rho = 0.77 \log_{10}(V_s) + 0.15
\]  

(6)

\( V_p \) and \( V_s \) are the P-wave and S-wave velocities, respectively. \( \rho \) is the density, and \( h \) is the depth. In the inversion process using Monte Carlo algorithm, the values of \( V_p \), \( V_s \), \( \rho \), and \( h \) always change to get the best model (lower misfit or equal to the previous iteration), while the values of \( Q_p \) and \( Q_s \) are fixed. In the inversion, the HVSR curve is assumed to be a reconstruction from body waves. The final result of the inversion process is a 1-D graphic of the relationship between \( V_s \) and depth. Figure 3 shows the results of the inversion process using OpenHVSR software.

| \( V_p \) (ms\(^{-1}\)) | \( V_s \) (ms\(^{-1}\)) | \( \rho \) (g.cm\(^{-3}\)) | \( h \) (m) | \( Q_p \) | \( Q_s \) |
|-----------------|-----------------|-----------------|---------|---------|---------|
| 233             | 200             | 1.9             | 5       | 10      | 5       |
| 929             | 800             | 2.4             | 6       | 20      | 10      |
| 1625            | 1400            | 2.6             | 11      | 30      | 15      |
| 2321            | 2000            | 2.7             | 28      | 40      | 20      |
| 3017            | 2600            | 2.8             | 94      | 50      | 25      |
| 3713            | 3200            | 2.9             | 999     | 999     | 999     |

The values of \( V_s \) generated from the inversion process were then interpolated to obtain the distribution of \( V_s \) on a two-dimensional (2-D) cross-section. Furthermore, the contrast of \( V_s \) is used to identify the presence of the Grindulu fault and other faults. Based on the contrast of \( V_s \) and considering the geological conditions in Pacitan area, the existence of several faults was identified as shown in Figure 4. Several faults were discovered in the study area including Grindulu Fault, Karangrejo Fault, Kayuwayang Fault, Tegalombo Fault, and other unknown faults.

A fault has a boundary area between the hanging wall and footwall. The boundary area will be filled with fluid and other materials, so there are different values of \( V_s \). Based on this condition, a contrast of \( V_s \) values can be interpreted as a fault, by considering the geological conditions.

![Figure 3. Result of the inversion process using OpenHVSR software.](image-url)
Figure 4. Several faults detected by the distribution of $V_s$ (a) on line 1 and (b) on line 2.

5. Conclusions
This study has attempted to show that a fault can be identified using a contrast of shear wave velocity ($V_s$), while the value of $V_s$ is generated from the inversion of the HVSR curve. Based on the results of the study, a contrast of $V_s$ is proven to be able to identify the presence of a fault. This must be supported by adequate geological information. Geological information is also needed in determining $V_s$ as the initial value in the model parameters. As the final result, four faults were identified including Grindulu Fault, Karangrejo Fault, Kayuwayang Fault, and Tegalombo Fault.

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