Investigation of Site Condition Using Elliptical Curve Inversion from Horizontal-to-Vertical Spectral Ratio (HVSR)

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Abstract. This study aims to investigate site conditions based on the dominant period and elliptical curve inversion of Horizontal-to-Vertical Spectral Ratio (HVSR). The data were taken using a seismometer portable short period in the minimum time span of data retrieval for 30 minutes. The Nakamura method as known as Horizontal-to-Vertical Spectral Ratio (HVSR) is used to obtain the value of the dominant frequency and amplification factor. The dominant frequency is changed to the dominant period which can indicate the type of soil. HVSR processing use Geopsy software with a guide from the SESAME Project. The results of processing show that the dominant frequency and the amplification factor. In Geopsy there are several modules and packages. This processing uses TFA Module and Max2curve Package and Dinver Package. Waveform can be inversed based on the elliptical curve of HVSR model to produce a shear wave velocity model (Vs) uses that modules and packages. From the velocity model, we can know Vs30 to determine the type of soil layer. The shear wave velocity model obtained can show the estimation of sediment thickness in the area under investigation.

1. Introduction
The data used in this study were obtained from 20 micro-tremor measurement points in the City of Sleman, Yogyakarta. Micro-tremor measurements use the Seismograph Short Time Seismograph (TDS) seismograph with a recording time span of 50 minutes. It takes 30 minutes to record the processed waveform to get the lowest base frequency of 0.2 Hz as expected results [1]. The recording process is extended from the recommended time in order to eliminate interference during the recording process in waveform data processing. Micro-tremor records can be used to obtain dominant frequency values that indicate the type of soil and the amplification factor. In addition, the inversion of the ellipticity curve of HVSR can be inversed to obtain subsurface velocity models.

The thickness of sediments in Sleman also has the potential to increase due to the volcanic material of Merapi carried by rainwater which is often called cold lava. In line with its activities to date, Merapi has deposited the material in large volumes, shutting out the stagnant water environment to dry, while at the foot of the volcano there is a local development of paleo-geomorphology which is laterally continuous[2]. Information on the thickness of the sediment can be used as a basis in making buildings and determining the area to be used as a development site. The middle of bedrock and volcanic deposits, in some locations black clay deposits are deposited in thicknesses varying from 1.5-20 m [2]. There are several geophysical methods that are often used to identify shallow subsurface structures
such as refraction, spatial autocorrelation (SPAC), Standard Penetration Test (SPT), and bore-hole. In this research, the HVSR study is used, which then values the dominant frequency and the amplification factor in inversion to get the subsurface velocity profile. The velocity profile can interpret subsurface structures. This method was first performed by Ibs-von Seht and Wohlenberg in 1999 to estimate the thickness carried out in the river delta of the Cologne region (Germany) [3]. The HVSR inversion method to identify subsurface has an advantage in time and energy when collecting data in the field. The weakness of this method is the high level of subjectivity. For this reason, a complete literacy study is needed to get reliable results.

![Figure 1. The Sleman region is dominated by igneous and sediments rocks from Mount Merapi. There are Merapi sediments with rose geometry, contemporary Merapi sediments, and young pyroclastic sediments. Modified from Peta GeologiLembar Yogyakarta [4]](image)

This study purposes to identify regional conditions based on soil types and subsurface structures using the dominant period and HVSR inversion methods. It is expected that the classification of soil types from the dominant period and HVSR inversion can be used as an alternative to the bore-hole method so as to reduce costs and labor. In addition, this method can also be used for data collection in densely populated areas because it does not require large tracts of land or perforating the surface of the land. Limitation problems in this study include determining the dominant period, identifying sediment thickness, and determining the type of soil. The hypothesis of this study is the classification of soil types from the dominant period value has the same results as the inversion of the HVSR curve based on the reference to the classification of soil types used, as well as the classification of soil types is influenced by sediment thickness.
2. Method
Data were collected at coordinates 110.307° - 110.420° E and 7.631° - 7.734° N. The study area has an elevation of 230 - 585 meters. The area of research carried out is not an area, but only a point to which subsurface conditions are known. Micro-tremor measurements using the Short Period Seismograph (TDS) with a recording time span of 50 minutes. Even though, it takes 30 minutes of the recorded process to get the lowest basic frequency of 0.2 Hz as expected results [1]. Another 20 minutes to anticipate the lack of window length due to the spike being removed.

![Figure 2. Micro-tremor data collection points [5]](image)

Processing to get the HVSR amplitude spectrum using Geopsy. Signals that are not stationary are removed by applying the STA/LTA Anti-triggering Algorithm. Comparison of Short-Term Average with Long-Term Average (STA/LTA) ranges from 0.2 to 2.5. The spectrum is calculated in every 25 seconds of the whole signal divided into windows. Tapering is done with a cosine function of 5%. The signal recording from the time order is converted into frequency order by the Fast Fourier Transform (FFT) process. The process changes the shape of the signal recording into an amplitude spectrum so that the dominant frequency value can be known. The spectrum of the two horizontal components is consulted. Then the H / V spectrum ratio is calculated for each window [6].

\[
A(f)_{\text{horizontal}} = \sqrt{A(f)_{EW}^2 + A(f)_{NS}^2}
\]

\[
HVSR = \frac{A(f)_{\text{horizontal}}}{A(f)_{\text{vertical}}}
\]  

(1)
The HVSR curve is calculated in the frequency range of 0.5 - 20 Hz. The results of the signal recording are used to get the value of the dominant frequency and amplification factor. The dominant frequency value and amplification factor are used to get the subsurface profile. The approach uses a single layer model formed by a low-speed layer over a semi-infinite space [3]. In this model, the relationship between the dominant frequency of HVSR, $f_0$, and the thickness of the layer, $h$, is

$$h = \frac{V_s}{4A_0f_0}$$  \hspace{1cm} (2)

The difference in shear wave velocity in the bedrock, $V_{SB}$, with the velocity in the upper layer, $V_s$, can be related to the HVSR amplification factor, $A_0$, which can be written as

$$A_0 = \frac{V_{SB}}{V_s}$$ \hspace{1cm} (3)

So that the thickness of the layer, $h$, can be related to the dominant frequency value, $f_0$, and the amplification factor, $A_0$, HVSR with the shear wave velocity value in the bedrock, $V_{SB}$, is known. Then it can be written by the equation:

$$h = \frac{V_{SB}}{4A_0f_0}$$ \hspace{1cm} (4)

The ellipticity of Rayleigh surface waves is inversed to investigate shallow subsurface structures. Rayleigh's ellipticity is calculated using the Time-Frequency Analysis (TFA) Module from Geopsy and this output file in .max. Wavelet parameters are calculated in the frequency range 0.1 - 10 Hz. To get the shallow subsurface structure from Rayleigh elliptic inversion, a conditional Neighborhood Algorithm is used that is implemented in Geopsy [7]. Not all signals can be processed in the TFA Module due to the availability of recorded Rayleigh waves.

Figure 3. The rayleigh ellipticity curve obtained from the TFA Module and can be seen in the Max2curve Package and this output file is .hv format.
Rayleigh elliptic curves are inverted using the DinverPackage from Geopsy and this output file is .dinver format. In this process, there are parameters as a reference for the inversion process. These parameters include compression wave velocity ($V_P$), Poisson-ratio, shear wave velocity ($V_S$), and density. Inversion of subsurface structures is nonlinear with information exchange between velocity and thickness of the medium for data compression wave velocity ($V_P$) and shear wave velocity ($V_S$) [7]. Parameter values are determined based on an ideal subsurface velocity profile model. The speed value will increase in proportion to the addition of depth. In this study, an initial model of subsurface bedding was used in three layers. Determination of the number of layers takes into account natural events in the study area so that the subsurface structure consists of bedrock, old sediments, and young sediments (lava and pyroclastic).
After the dominant period, values and velocity model profiles are obtained, the type of soil can be determined. Zhao et al. used the HVSR method to identify soil types based on average spectrum ratios over a wide range of spectrum periods [8]. The geological conditions in Indonesia have similar conditions to Japan because there are many active faults and volcanoes. Under these conditions, the determination of soil type refers to the National Earthquake Hazard Reduction Program (NEHRP) which is also used by Japan to design earthquake-resistant buildings. Dominant period values and shear wave velocity profiles are used to determine soil types based on the NEHRP table.

### Table 1. The Definition of Soil Type used by Japan. [9]

| Type of Soil | Dominant Period | The average velocity of the Shear Wave | Soil Type by NEHRP |
|--------------|-----------------|---------------------------------------|--------------------|
| Stone        | $T_0 < 0.2s$    | $V_{s30} > 600$ m/s                   | A + B              |
| Hard Soil    | $0.2s \leq T_0 < 0.4s$ | $300$ m/s $< V_{s30} \leq 600$ m/s | C                  |
| Medium Soil  | $0.4s \leq T_0 < 0.6s$ | $200$ m/s $< V_{s30} \leq 300$ m/s | D                  |
| Soft Soil    | $T_0 \geq 0.6s$ | $V_{s30} \leq 200$ m/s               | E                  |

Sediment thickness can be determined from the speed profile. The value of the shear wave velocity, $V_s$, in the bedrock is more than 750 m/s [10]. If referring to the NEHRP table, the value of $V_s$ is 600 m/s. In this study, the thickness of the sediment was calculated from the surface until the layers which started to have $V_s$ of more than 750 m/s.

### 3. Results and Discussion

The results of the HVSR with the FFT process of 20 points have a dominant period range between 0.065368 s to 1.589825 s. Determination of the dominant frequency of the HVSR can also be determined manually if the results of the software are not appropriate. Such problems occur when the spectrum has more than one peak. The soil type is dominated by soft soil, Class E, although the point under study is not located in a basin.

Not all data can be processed to get speed profiles. That was caused by the recorded Rayleigh waves that were less dominant. From 20 data inversion processes, there are 15 velocity profile data that can be generated. Signal quality can be known when processed in the Max2curve Package.

Sediment thickness identification is only performed on data that have a shear wave velocity profile. There are 15 points that can be analyzed to understand the thickness of the sediment. The average velocity of shear waves at 30 meters depth can be calculated from the shear wave velocity profile. Mathematically can be written:

$$\frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} V_{s_i}}$$

Where $d_i$ is the thickness of each layer $i$ in meters, $V_{s_i}$ is the shear wave velocity in layer $i$ expressed in m/s, and $\sum_{i=1}^{n} d_i$ is the observed subsurface depth. To find $V_{s30}$, the subsurface depth under review is 30 meters. Then the equation above can be written as:

$$V_{s30} = \frac{30}{\sum_{i=1}^{n} d_i}$$
The results obtained from the HVSR version are as follows:

| Point | Elevation (m) | Latitude (°LS) | Longitude (°BT) | Sediment thickness (m) | $V_s$30 (m/s) | Type of Soil ($V_s$30) | Type of Soil ($T_0$) |
|-------|--------------|----------------|----------------|------------------------|--------------|------------------------|------------------------|
| Y-1   | 369          | -7.6494        | 110.3318       | 100                    | 100          | E                      | E                      |
| Y-2   | 414          | -7.6498        | 110.3513       | 98                     | 108.3333     | E                      | E                      |
| Y-3   | 444          | -7.64884       | 110.3695       | N/A                    | N/A          | N/A                    | E                      |
| Y-4   | 469          | -7.6494        | 110.3867       | 18                     | 604.3956     | A+B                    | A+B                    |
| Y-5   | 506          | -7.6503        | 110.4057       | 94                     | 115.3846     | E                      | E                      |
| Y-6   | 322          | -7.6691        | 110.3314       | 94                     | 100          | E                      | E                      |
| Y-7   | 356          | -7.6671        | 110.3514       | N/A                    | N/A          | N/A                    | E                      |
| Y-8   | 366          | -7.6682        | 110.3703       | 44                     | 193.7591     | E                      | E                      |
| Y-9   | 409          | -7.666         | 110.37         | >104                   | 87.2093      | E                      | E                      |
| Y-10  | 426          | -7.661         | 110.4049       | 96                     | 111.1111     | E                      | E                      |
| Y-11  | 259          | -7.68795       | 110.3343       | 76                     | 325          | C                      | C                      |
| Y-12  | 329          | -7.6855        | 110.3664       | N/A                    | N/A          | N/A                    | E                      |
| Y-13  | 230          | -7.70677       | 110.3311       | 44                     | 250          | D                      | E                      |
| Y-14  | 261          | -7.7031        | 110.3513       | 23                     | 343.8865     | C                      | A+B                    |
| Y-15  | 277          | -7.7032        | 110.3698       | 98                     | 100          | E                      | E                      |
| Y-16  | 267          | -7.7342        | 110.42         | 100                    | 100          | E                      | E                      |
| Y-17  | 301          | -7.70317       | 110.4052       | 20                     | 605.2402     | A+B                    | A+B                    |
| Y-18  | 509          | -7.6324        | 110.3635       | N/A                    | N/A          | N/A                    | C                      |
| Y-19  | 585          | -7.63102       | 110.4048       | N/A                    | N/A          | N/A                    | E                      |
| Y-20  | 293          | -7.65287       | 110.307        | 96                     | 109.7561     | E                      | E                      |

From the table above, there are two points that have different types of soil classification results. The two points indicate the classification of soil types from $V_s$30 and $T_0$ to differ by one level. At point Y-4 it has a rock soil type, Class A+B, which corresponds to the geological map (Fig. 1) because there are present-day Merapi deposits (pyroclastic and lava). Points Y-11, Y-13, and Y-14 are known to have hard and medium soil types, Class C and D. When viewed from elevation values, these three points are the three lowest points compared to other points. Based on Google Earth, 14 it is known that the point is a rice field area on the roadside. In this study, there was an anomaly at point Y-17 because the rock soil type, Class A+B, was found in residential areas. Further review is needed to find out subsurface conditions at point Y-17. At the other 15 points, classified soil types are soft soils, Class E. The average thickness of sediments in soft soils from known shear wave velocity profile data is 98 meters.
Figure 6. The velocity profile of the S wave until 104 m of depth which represents the type of soil based on the value of Vs30 where Y-4 is A+B class, Y-14 is C class, Y-13 is D class, and Y-15 is E class.

4. Conclusion
The results of classifying soil types based on dominant periods and shear wave velocity profiles have the same 86.667% results. This shows the NEHRP classification table suitable for use in Indonesia. Soil type is affected by sediment thickness. The elevation of a place does not fully determine the type of soil because nature activity and human activity can influence the sedimentation process. In data processing, not all micro-tremor records can be inversed. Surface waves, especially Rayleigh waves, can be utilized in the inversion process by using a Dinver Package from Geopsy. Signal quality can be known in the Max2curve Package.
Author Contributions
All authors contributed equally to this work. All authors have reviewed the final version of the manuscript and approved it for publication.

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