Horizontal-vertical Spectral Ratio Method in Microtremor to Estimate Engineering Bedrock Thickness at Sedati Mud Volcano

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Abstract. Based on field study, Sedati Mud Volcano located in a line with Gunung Anyar Mud Volcano and occurred by increased pressure in the compression area and rapid loss of gas. The combination of both fast-growing constructions of infrastructures and the presence of the mud volcanoes brings new challenges in Sidoarjo city. The purpose of this scientific research is to determine the sedimentary thickness around Sedati mud volcano. Only a few data show real amplitude spectrum, which represent high contrast impedance. At some point, there are several peaks indicating the presence of contrast impedance between layers. Based on 20 processed data, Sedati Mud Volcano has a 30 – 70m engineering bedrock thickness and natural frequency between 0.5 until 14.4 Hz. The enhancement of natural frequency tends to occur along decrement of layer thickness in the upper basement layer. The result shows the natural frequency parameter and its amplification is slightly variated around Sedati Mud Volcano, as caused by sedimentary lateral depth variation and/or the presence of variation on existing rock. Further analysis indicates a fault inside the area of mud volcano as possible reason behind the occurring mudflow.

1. Introduction
Mud Volcano has become a popular discussion lately, especially after the tragedy of Lapindo Mud Volcano in Sidoarjo. Although, it is still debated for the cause of its eruption.

Mud volcanoes phenomenon indicates a strong active tectonic setting. It refers to the expression of the natural topography of the volcano cone-shaped formations created by geological factors and the released sedimentary liquid, clay fragment, liquid, and gas. Most of the released gases are methane, with some carbon dioxide and nitrogen [1][2].

Many cases of earthquakes show that the damage depends on topography and the surface geology. The earthquake that should not have a destructive character can be dangerous due to the amplification of the earthquake. One method that is used for mapping prone areas to earthquake damage (seismic microzonation) is microtremor method. This passive geophysical method shows how the influence of the effect in the earthquake zone and the soft soil of the building in an area [3].

The purpose of this scientific research is to determine the sedimentary thickness by using frequency of spectral ratio from microtremor data. Thus, microzonation may explain the value of earthquake vulnerability in each region.
The thickness of engineering bedrock is one aspect that needs to be considered in determining the location of construction project. As it will affect the durability and safety of the building infrastructure. Sidoarjo is a city that is growing rapidly nowadays. Hence, it takes geophysical information relating to the scope of the geotechnical planning for urban infrastructure such as roads, bridges, housing, etc. This research evaluate the dynamic characteristics of soil from the wave propagation. Some physical parameters can be seen from the propagation of the wave is the wave velocity, amplitude variations, wave period and the natural frequencies [4].

2. Methodology

2.1. HVSR Method

Amplitude Horizontal to Vertical Fourier Spectral Ratio Method or HVSR also known as Quasi-Transfer Spectra or QTS was first introduced by Yutaka Nakamura in 1989 [4]. We used this method to estimate the natural frequency and amplification of the regional geology from microtremor data. Throughout the development, this method arose its capability to estimate the vulnerability index for land and building vulnerability index [5][6].

The main parameter from HVSR is the natural frequency or f0 and amplification. Measured HVSR in the soil applied in order to characterize the region, natural frequency and amplification to which corresponds to subsurface physical parameters [7].

In connection with HVSR to local geological characterization, one should understand the factors effecting the subsurface parameters that contribute to change in the natural frequency (f0) and amplification. This serves three purposes. First, the correctly interpretation of microzonation with using HVSR. Second, determining the cause of the damage will be determined with certainty. Third, as a consideration in extracting the subsurface parameter from HVSR curve. [8] introduced the application of HVSR equation for vibration measurement at the surface.

HVSR analysis method as developed by [4], calculates the ratio of Fourier spectrum of the microtremor signal from horizontal component to the vertical component. The result of HVSR analysis will show a peak in the predominant frequency spectrum [4]. Dominant frequency (f0) and the amplification factor (A) describes the dynamic characteristics of the land resulting from the analysis of HVSR [9].

One of the main aspect of using microtremor in the study area is the rarity of occurring earthquake. Hence, the research only requires ambient noise from around the study area. Furthermore, this method does not require any use of costly and time-consuming methods such as borehole or seismic methods.

2.2. Engineering Bedrock Thickness Calculation

[10] Gives an equation used to determine the thickness value of engineering bedrock layer. This research utilizes Equation (1) to calculate thickness of layer of soft sedimentary bedrock (m). The process starts from determining the value of Vs30 from USGS with respect to the research location to which corresponds with Vo, fr or dominant natural frequency from microtremor data and X as exponential factor.

\[
m = \frac{V_o(1-X)}{4f_r} + 1^{\frac{1}{2(1-X)}} - 1
\]  

2.3. Data Acquisition

In this research, we acquired 20 data from the Sedati Mud Volcano Area. Each data was taken through 40-minute and 60-minute recording time. This difference in recording time provided simpler time window picking process and obtaining better f0 value.
3. Result and Analysis

In this study, HVSR curve is evaluated based on [11] criteria. This evaluation determines whether the H/V curve and peak is reliable or unusable. The process will determine the accuracy and reliability of natural frequency obtained.

We processed the data by using 20 – 50 second window length. Based on [11] suggestion, data should have minimal value of lw = 10/f0, with lw by means of window length and f0 as resonance frequency. Thus, each window provided the 10 minimum significant cycle.

The result of processing 20 data yields predominant frequency around 0.5 Hz – 14.4 Hz. HVSR curves and f0 value are divided into two categories, the first category can be seen in figure 2 which have a wide H/V value at the beginning of the data and narrowed at the end. Peak frequency of first category has a range values between 0.5 Hz – 0.8 Hz. The location of the measurement also has the same characteristic, at point 1, 2, 3, and 11. According to [11], H/V curve of first category is the result of measurement on natural soil.

The second category is H/V curve with low value at the beginning of the data and getting higher at the end of the data. This HVSR curve has a peak frequency between 7 Hz – 16 Hz. Based on geological condition of measurement locations, point 6-10 and 15-19 are located at the edge of Sedati Mud Volcano crater. Second category of HVSR curve indicated that measurements was conducted on a thin surface layer [12], research conducted by [13] also proved that microtremor data with more than

![Figure 1. Line acquisitions shown in four red line, moving from West to East.](image)

![Figure 2. H/V curve for first category has a wide H/V value at the beginning and narrows at the end of the curve. This type of H/V curve occurred at first measurement (a), second (b), third (c), and the eleventh (d). This type of curve is listed on [11] as natural soil H/V curve (e).](image)
10 Hz indicate a thin surface layer. Nevertheless, data with f0 value of more than 10 Hz can’t be used as the microtremor’s maximum frequency is 10 Hz.

The remaining data is not included in the two categories because it has its own characteristics on its curve shape and predominance frequency. Point 4 has similarities as in category 2, the difference is the amount of environmental noise occurred at point 4 where the data obtained does not have a clear peak and constant form. Point 5 is the only point with a clear peak; we assumed that the measurement point is not in geological area within the mud volcano. Point 12 has similar characteristics to category 2; the difference lies in the different value of frequencies (0.781 Hz). The differences occur on the location of cracked and split ground, so an optimal vertical wave was not recorded. Furthermore, data measured near the mud volcano crater has curve similar to point 12, with H/V range of values between 4 – 8 with 0.6 Hz and 0.8 Hz frequency, respectively. Low frequencies were caused by the depth of layer in the Sedati Mud Volcano crater.

Figure 3. H/V curve for second category has a narrow H/V value at the beginning and peaks at the end of the curve. This type of H/V curve occurred at sixth measurement (a), seventh (b), eight (c), ninth (d), tenth (e), fifteenth (f), sixteenth (g), seventeenth (h), eighteenth (i), and nineteenth (j). This type of curve is listed on [12][13] as thin surface layer H/V curve (k).

As valid microtremor data has a natural frequency value less than 10 (f0 < 10 Hz) and with amplification factor more than 2 (A > 2), only several f0 and A0 data can be used. In these measurements, only 9 out of 20 data meet these requirements. Other 7 data is unused due to natural frequencies exceeding 10 Hz and 4 other data due to amplification value below 2. Unused data due to invalid natural frequency and amplification, can be seen In table 2 as labelled with yellow and pink colour, respectively.
Figure 4. Uncategorized HVSR curve because of its own characteristic, fourth measurement (a), fifth (b), twelve (c), thirteenth (d), and fourteenth (e).

Figure 5. Measurement location for point 12 (5a) and point 9 (5b), many other areas have same geological surface condition which affecting data quality and resulting the second category or unclassified HVSR curve.

From 9 reliable data, engineering bedrock thickness maps is created using Vs30 and coordinate point of measurements. As can be seen from figure 6 that soft sedimentary layer or engineering bedrock has ±70m thickness on the east side of measurements (point 1, 6, 11, and 16) and diminish towards the west side. Figure 7 is slicing map from figure 6 to show the conditions below the surface. Correlation with [10] data lies in the presence of southwest – northeast regional trend. Correlation between the two data took place in locations where the regional trend is directing towards southwest - northeast (figure 6) which indicates the possibility of continuity of Watukosek fault that crosses this area. In figure 6, contour line for 70 – 78m depth symbolizes the fault trending southwest – northeast. From the interpretation of previous research [4][10] it can be seen that Watukosek fault have continuity heading towards Madura Island, and the location of the centre point of the mud volcano bursts Gunung Sedati located on the eastern side of Watukosek fault line.

Table 1. Used data for measuring engineering bedrock thickness labelled with blue colour, while yellow colour represents unreliable data because it has f0>10 Hz, and pink colour represents unreliable data because it has A0>2.
4. Conclusion
Through measurements of micro tremor conducted at Sedati mud volcano, we concluded:
- Duration of measurements on the mud volcano area should be more than 40 minutes as in point 2, 3, 11, 13, and 14 to obtain reliable and clear data.
- From the calculation of HVSR, the thickness of engineering bedrock layer of mud volcanoes Sedati is 30-70 m.
- Regional trend at depth of 68-70 m indicates the possibility of continuity of Watukosek fault with Southwest - Northeast trend direction in the research area of the mud volcano Sedati.

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