Estimating shear wave velocity (Vs30) of East Java, Indonesia, using ambient noise inversion of horizontal to vertical spectral ratio (HVSR)

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Abstract. The shear wave velocity on average to a depth of 30 m (Vs30) is an important parameter for seismic hazard assessment. Vs30 can identify soil dynamic characteristics that can be used to seismic hazards mitigation efforts. East Java is one of the provinces in Indonesia that has high geological disaster potential. Therefore, a study of earthquake risk mitigation strategies must be carried out as a disaster mitigation effort. One of the ways to determine soil characteristics is to estimate the shear wave velocity. This study aims to determine the average shear wave velocity (Vs30) to obtain information on the vulnerability of soil conditions in East Java. We use stationary seismograph data from Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG), German Research Centre for Geosciences (GFZ) temporary seismograph and secondary data from seismic waveform portable seismographs installed independently in East Java. This study uses the horizontal and vertical ambient noise inversion method. One-dimensional wave velocity models are obtained from Monte Carlo simulations based on the best misfit values. Vs30 East Java values ranged from 168–788 m/s with sediment thickness ranging from 10 meters to more than 200 meters. Based on the classification of soil types, in the northern part of East Java is dominated by the type of soft soil (SE) to hard soil (SC). In the southern part of eastern Java is dominated by medium soil (SD) to hard rock (SA). The northern part of East Java, especially in the Kendeng zone is dominated by low shear wave velocity. Lowest Vs30 can be seen in Sidoarjo, Surabaya, Mojokerto, Jombang, Gresik, Lamongan, Nganjuk, Madiun, Ngawi, Bojonegoro, Probolinggo and the southern part of the Madura Island. The low shear wave velocity (Vs30) is associated with sediment layers and high shear wave velocity (Vs30) is associated with hilly areas and transition zones.

Keywords: Ambient noise, east java, inversion HVSR, Vs30

1. Introduction

East Java is one of the provinces in Indonesia that has high geological disaster potential. The existence of volcanoes in the south increases the disaster risk of earthquakes. The southern part of East Java is
Java subduction zone. Java subduction zone is the plate boundary between the Eurasian plate and the Indo-Australia plate, extending 1700 km from the Sunda Strait to the eastern part of Indonesia. Many large earthquakes occur in the subduction zone, especially in Megathrust and Benioff zones. The great earthquakes often occur in the Java subduction zone. The large earthquake has occurred in the southern part of Java Island, which generated a tsunami in 1994 with moment magnitude 7.8 and 2006 with moment magnitude 7.7 [1]. In the northern part of East Java presences of Flores back arc thrust fault, extending 300 km onshore into Java East along the Kendeng zone increases the level of earthquake vulnerability on the Java Island. This area often occurs shallow earthquakes that cause damage to buildings and casualties.

Based on demography, East Java is one of the provinces in Indonesia that has a high population. According to data from the Indonesian Agency for Central Statistics (BPS), the population of East Java in 2017 is 39,292,952 people. The high population density increases vulnerability to disasters. Therefore, East Java needs to get attention to seismic hazard assessment and seismic microzonation investigations. The effort that can be done is to study the characteristics of the local site effect.

Recently, Local site effect investigation can be determined through analysis of the recording of ambient noise signals. One method for analyzing ambient noise signals is the H/V method. H/V is a ratio of the horizontal to vertical spectrum of the ambient noise signal. This method can evaluate the characteristics of sediment layers (soil) [2]. One of the way to determine soil characteristics is to estimate the shear wave velocity. The shear wave velocity from the ground to a depth of 30 meters (Vs30) is an important parameter in determining soil characteristics. Geophysical methods present many methods for determining the shear waves Velocity (Vs30), one of which is ambient noise measurements.

Ambien noise is the ground vibration sourced from native such as ocean waves, wind, atmosphere, and human activities such as traffic, industry, etc. [3]. Ambient noise is defined as ground vibrations that are constantly sourced from resonating vibrations [4]. In this study, the ambient noise analysis uses the inverse H/V spectral ratio method. The ambient noise is a very efficient tool to evaluate the local site effect on seismic motion without needing other geological information [5].

The purpose of this study is to map the shear wave velocity on average to a depth of 30 m (Vs30) and classify soil types in the East Java region by utilizing the ambient noise horizontal to vertical spatial ratio inversion. The results of this mapping can be used as an effort to improve disaster preparedness.

2. Data and method

2.1. Data

In this study, we use stationary seismograph data from Indonesian Agency for Meteorological, Climatology and Geophysics and German Research Centre for Geosciences (GFZ) temporary seismograph. Data signal is downloaded per station from BMKG and GFZ data archives [6, 7]. We also use secondary data from seismic waveform portable seismographs installed independently. The interstation distances range from ~5 to ~40 km. Distribution of measurement locations can be seen in figure 1.

2.2. Method

In this paper using different seismometers of various type, so we removed the instrument in response to each seismogram. Ambient noise inversion data processing uses software dinver [8]. The result of inversion data processing is the 1D model of shear wave velocity per station. The first step in processing the data using dinver software is input the h/v curve data from the observations and initial model parameters such as P wave velocity, S wave velocity, Poisson ratio, and density [9]. The inversion process is done based on the inversion process from Monte Carlo techniques or conditional neighborhood algorithms [10].
Determination of the velocity model based on the misfit value (0 misfits < 1). If the resulting misfit value is still high (> 1), it is necessary to change the initial model parameters. Calculation of misfit uses equation 1 [11].

\[
\text{Misfit} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (D_i - M_i^2)/\sigma_i}
\]

Notation of equation 1 that N is the Number of Data. Di is Result of inversion. Mi is parameter model and \( \sigma \) is a standard deviation.

Calculation of shear wave velocity averaged to a depth of 30 m using equation 2 [12]. The results of the Vs30 calculation are then mapping and analyzed based on the aspect of structural and physiographic of East Java.

\[
Vs_{30} = \frac{30}{\sum_{i=1}^{N} (h_i/Vsi)}
\]

where N is the number of layers, \( h_i \) is the thickness of the first layer, and \( Vsi \) is the shear wave velocity in the layer.

In this study, the classification of soil types refers to the provisions made by the National Standardization Agency 1726 of 2012 concerning earthquake resistance planning procedures for structures of buildings and non-buildings. There is a classification of soil types shown in table 1.

![Seismometer distribution map](image)

**Figure 1.** Seismometer distribution map used in the research.

| Site Class | Type Rock  | Vs30 (m/s) |
|------------|------------|------------|
| SA         | Hard Rock  | > 1500     |
| SB         | Rock       | 750–1500   |
| SC         | Hard Soil  | 350–750    |
| SD         | Medium Soil| 175–350    |
| SE         | Soft Soil  | < 175      |

**Table 1.** Classification soil reference to SNI 1726 2012.
3. Results and discussion

3.1. Shear wave velocity map (Vs30) of East Java

The shear wave velocity from the ground to a depth of 30 meters (Vs30) is an important parameter in determining soil characteristics. Some researchers claim that amplification affects the building to a depth of 30 meters. Shear wave velocity is influenced by natural and topographic frequency values. The lower the natural frequency value, the lower the value of shear wave velocity [5]. The high topographic area indicated high shear wave velocity, while the low topographic area indicated low shear wave velocity.

This study calculates the average shear wave velocity to a depth of 30 m. The average shear wave velocity follows equation 2. Each point obtains a 1-D model of shear wave velocity, so we have 100 shear wave velocity models. The results of each point are interpolated to determine the distribution of shear wave velocity in East Java.

Figure 2 shows the results of ambient noise inversion of horizontal to vertical spectral ratio for shear wave velocities averaging to a depth of 30 m. The study area is divided into 3 zones, the southern part of East Java, the middle part of East Java, and the northern part of East Java. Based on physiographic, the southern part of East Java is the Southern Mountain zone, the middle part of East Java is the Kendeng zone, and the northern part is the Rembang zone. The kendeng zone is dominated by low shear wave velocities. These results indicate that this area is dominated by sedimentary layers. Lowest shear wave velocity can be seen in Sidoarjo, Surabaya, Mojokerto, Jombang, Gresik, Lamongan, Nganjuk, Madiun, Ngawi, Bojonegoro, Pasuruan, and Probolinggo. Shear wave velocities range from 160–300 m/s in this area. The kendeng zone is composed of a layer of unconsolidated sediment which is indicated by the alluvial presence in the east of this zone. The areas with low shear wave velocity have a high vulnerability, so development needs to be adjusted to the characteristics site effect of this area.

Figure 2. Shear wave velocity distribution map in East Java using HVSR inversion.
The northern part of East Java is included in the Rembang zone. The shear wave velocity of the Rembang zone is moderate. The presence of limestone and carbonate layers in the western part of this area indicates that the shear wave velocity is relatively higher than the Kendeng zone and lower than the Southern Mountain zone. This area is dominated by hard soil class (SC) and rocks class (SB), especially around Lasem Mountain.

The southern part of East Java includes Pacitan, Trenggalek, Tulungagung, Malang Lumajang, Jember and Banyuwangi included in the Southern Mountain zone. In general, the shear wave velocity is highest. These results indicate that this region is a hill and a transition zone. The presence of volcanoes indicates high shear wave velocities. Shear wave velocities range from 380 m/s to 788 m/s. Lumajang and Jember have lower shear wave velocities (Vs30 380–480 m/s). This area has a low topography and is dominated by silt and sand layers.

Madura is part of the developing zone. Low shear wave velocity in the southern part of Madura Island. Shear velocities range from 190 m/s to 380 m/s. The northern part of Madura is relatively higher shear wave velocity (Vs30 380–770 m/s).

This study compares the results of ambient noise and USGS inversion. USGS velocity data is obtained by downloading the shear wave velocity data from the United States Geological Survey (USGS) repository [13]. We use the same grid point as this research. The inversion shear wave velocity has similarities to the shear wave velocity of the USGS. The result of ambient noise and USGS inversion has a strong correlation as shown in figure 3.

Based on figure 4 the regression analysis shows that the correlation coefficient is 0.808. The results of the regression analysis indicate representative values of up to 80 percent. The High topography regions have high shear wave velocities and the low topographic regions have low shear wave velocity values. The high topographic region is composed of rock hard, compact, and has not undergone changes due to the deposition process, so the shear wave velocity in this region is high.

Figure 5 shows vertical shear wave velocity profiles beneath East Java. Cross-section cuts the research area from south to north. Cross-sections 1 and 2 show high shear wave velocity in the southern part of the cross-section. In the middle of the cross-section, the shear wave velocity is low. In the north part, the shear wave velocity is higher than the middle but lower than the south. In the middle of the cross-section is low shear wave velocity (Vs30 160–750 m) at a depth of 210 m. These results indicate that this area has thick sediment (h 100– more than 200 m). Low shear wave velocity is seen at latitude -7.50ºLs to 6.75ºLS.

Figure 3. Comparison of the shear wave velocity distribution of (a) HVSR inversion and (b) USGS.
Figure 4. Regression analysis to determine the correlation between Vs30 ambient noise inversion and Vs30 of USGS.

Figure 5. Vertical shear wave velocity profile from southern to northern of East Java direction.

Figure 6 shows a cross-section cut through three different zones. Cross-section A cuts the Rembang zone from the western to the eastern part of East Java. Cross-section B shows the profile vertical in the Kendeng zone below the middle part of East Java. Cross-section C cuts through the Southern Mountain zone from western to eastern part of East Java. The results of cross-sections A and B show the Rembang and Kendeng zones are dominated by low wave velocities. Shear wave velocity ranges from 160–750 m/s at a depth of 100 to 200 m. In this zone, the thickness of the sediment is estimated to be very thick. The existence of volcanic eruptions in Sidoarjo is a sign that this zone is covered with thick sediments. Martha et al. confirmed that the thickness of this zone sediment ranges from 8–11 km [14].

3.2. Classification soil map of East Java
An earthquake can cause damage to buildings and infrastructure, especially in East Java. for geotechnical investigations the classification of soil types is needed as a reference for development planning. The Indonesian standardization agency has made procedures for determining the classification of soil types based on the shear wave velocity calculation (table 1). Soil types are classified into soft soil (SE) with a value of Vs of less than 175 m/s, medium soil (SD) with a value of Vs 175 to less than 350 m/s, hard soil/soft rock (SC) with a value of Vs of more than 350 up to less than 750 m/s, rock (SB) with a value of more than 750 to less than 1500 m/s and hard rock (SA) with a value of Vs of more than 1500 m/s.
Figure 6. Vertical shear wave velocity profile from west to east direction.

Figure 7. Map of classification soil in East Java based on SNI 1726:2016.

Generally, in the northern part of East Java is dominated by soft soil (SE) to hard soil (SC). While in the Southern part of East Java is dominated by hard soil type (SC) to hard rock (SA). Figure 7 shows the distribution map of classification soil in East Java based on SNI 1726:2012 [12]. Geomorphologically, the southern part of East Java is located in hilly and mountainous areas so that the rock structure is getting harder while the northern part of East Java is dominated by sedimentary layers composed of soft rock. When an earthquake occurs, the area composed of soft soil material will be amplified. This can cause shocks that are felt to be getting stronger.

4. Conclusion
The results of shear wave velocity mapping to a depth of 30 m (Vs30) based on ambient noise inversion of horizontal to vertical spectral ratio (HVSR) show the northern part of East Java consisting of Kendeng Zone and Rembang Zone having lower shear wave velocity values (Vs30)
ranging from 163–410 m/s. The southern part of East Java consists of the Southern Mountains zone and the Volcanic Bow has a higher shear wave velocity (Vs30) around 320–788 m/s. Madura Island is included in the Rembang zone which has a low shear wave velocity (Vs30) in the southern part of Madura. Based on the classification of soil types, the northern part of East Java is dominated by the type of soft soil (SE) to hard soil/soft rocks (SC). The southern part of East Java is dominated by medium soil (SD) to hard rock (SA). The low shear wave velocity (Vs30) is associated with sediment layers and high shear wave velocity (Vs30) is associated with hilly areas and transition zones.

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