Synthetic Modeling of Ambient Seismic Noise Tomography Data

Firman Syaifuddin,1, 2,* Andri Dian Nugraha,1 Zulfakriza,1 Shindy Rosalia,1

1 Institut Teknologi Bandung (ITB), Campus ITB, Jl. Ganesha No.10, Bandung, Jawa Barat, 40132, Indonesia.
2 Institut Teknologi Sepuluh Nopember (ITS), Campus ITS, Sukolilo, Jl. Raya ITS, Keputih, Surabaya, Jawa Timur, 60117, Indonesia.

*Corresponding author: firmansyaifuddinakbar@gmail.com

Abstract. Ambient seismic noise tomography is one of the most widely used methods in seismological studies today, especially after a comprehensive Earth noise model was published and noise analysis was performed on the IRIS Global Seismographic Network. Furthermore, the Power Spectral Density technique was introduced to identify background seismic noise in the United States. Many studies have been carried out using the ambient seismic noise tomography method which can be broadly grouped into several groups based on the objectives and research targets, such as to determine the structure of the earth's crust and the upper mantle, to know the thickness of the sedimentary basins, to know the tectonic settings and geological structures, to know volcanic systems and geothermal systems, knowing near-surface geological features and as a monitoring effort the Ambient Noise Tomography method carried out by repeated measurements or time lapse. In this study, we investigate the characteristics of the ambient noise seismic tomography method, both its advantages and limitations of the method by utilizing synthetic data modeling using a simple geological model. Synthetic data is generated based on 1D dispersion curve forward modeling and the forward modeling of surface waves travel time for each period, which is then convoluted with the wavelets of each periods, then doing reverse correlation using a reference signal to produce synthetic recording data. We found that the estimate target depth and vertical resolution depend on the recorded data periods and the synthetic data modeling can be used as a basis in determining the acquisition design.

Keywords: Synthetic modelling, ambient noise seismic tomography

1. Introduction
The Ambient seismic noise tomography is one of the most widely used methods in seismological studies today, especially after a comprehensive Earth noise model was published [1] and noise analysis was carried out on the IRIS Global Seismographic Network [2], then Furthermore, the Power Spectral Density technique was introduced to identify background seismic noise on the United States Plain [3]. The use of cross-correlation techniques began to be used in an effort to extract the Green Function on ambient seismic noise data for a period of 10 to 150 seconds to describe the conditions of the earth's crust and the upper mantle in the United States [4], the same technique was also used to know the changes in seismic wave velocity values around Mount Merapi [5].

Many studies using the ambient seismic noise tomography method have been carried out which in general can be grouped into several groups based on research objectives and objectives, including to
determine the structure of the earth's crust and the upper mantle, to determine the thickness of the sedimentary basins, knowing tectonic settings and geological structures, knowing volcanic systems and geothermal systems, knowing near-surface geological features, and as an effort to monitor the Ambient Noise Tomography method by repeated measurements or time-lapses.

From the results of the research that has been done, it provides subsurface information according to the desired target, but not many have discussed the limitations of this method such as the relationship between the target depth and the seismic noise data period used in this method. This paper will discuss the relationship between the target depth and the seismic noise data period used so that it is in accordance with the desired resolution with the synthetic modeling approach.

2. Method
2.1. Ambient Seismic Noise Synthetic Modeling
Ambient seismic noise tomography data processing procedures are described by [6] in detail which consists of 4 main stages, data preparation for each station, cross-correlation and temporal stacking, dispersion curve estimation using frequency-time analysis (FTAN) techniques, and data quality control. Referring to the data processing procedure for ambient seismic noise tomography described by [6], the synthetic modeling process for ambient seismic noise data is carried out using reverse flow diagrams described by [6]. The flow chart for synthetic ambient seismic noise data generation is shown in Figure 1.

![Figure 1. Flow chart for synthetic ambient seismic noise data generation.](image-url)
2.1.1. Geological Model Building
The synthetic modeling process begins with making a geological model accompanied by physical properties such as P wave velocity, S wave velocity, and the density of the model. In this study, the geological model used is a simple flat layer model with the S wave velocity as the main input based on the equation function $V_s(Z) = V_s0 + kZ$ [7], with $V_s0 = 300$ m/s and $k = 0.5$, where $V_s0$ is reference S velocity at surface, $K$ is gradient, and $Z$ is depth, with a depth of 8,000 m and a lateral distance of 30 km. Vp is obtained based on the Vp / Vs relationship of 1.7 and the density is converted from the Vp value. A simple geological model can be seen in Figure 2.

![Figure 2. Simple flat layer geological model for Vs, Vp and density models, respectively.](image)

2.1.2. Dispersion Curve Modeling
1D forward modeling dispersion curve is generated using the dispersion curve function obtained by mat_disperse referring to the algorithm developed by [8] and [9]. The 1D curve is modeled at each observation station with intervals of 1000 meters and a period of 0.5, 1, 2, 4, 5, 6, 8, 10, 15, 20, 30, 40, 50 and 100 seconds. The 1D dispersion curve at station 31 can be seen in Figure 3a and in Figure 3b plot the group velocity model at each station as a function of the period.
2.1.3. Travel Time Forward Modeling & Wavelet Convolution

Based on the group velocity model, the travel time for surface wave propagation is calculated based on the distance between stations. In Figure 4 is a plot of the wave propagation time as a function of the period.

The arrival time of the surface waves is calculated based on the travel time surface wave model in each period and a certain distance which is convoluted with the wavelet of each period. Figure 5 shows the wavelets for a period of 100 seconds, 10 seconds, and 1 second, as well as the convolution results for each station.
2.1.4. Reverse Correlation and Stacking

The Green function extraction in data processing using the ambient seismic noise tomography method is usually approached by cross-correlation techniques, so that the forward modeling process is carried out in the opposite direction. The reverse cross-correlation process is carried out in the frequency domain by modifying the cross-correlation function in the frequency domain used [10]. In principle, the reverse cross-correlation process is to produce one input between two cross-correlated signals, results of convoluted wavelet with travel time in each period and distance considered as a result of cross-correlation. The reverse cross-correlation resulting desire signal which then considered to be synthetic ambient seismic noise data after stacking in all periods used. Figure 6 shows an example of the reverse cross-correlation results for the 1 second period. Figure 7 is the result of the inverting cross-correlation of each period which is then stacked to produce the desired signal as synthetic ambient seismic noise data.

**Figure 5.** Convoluted wavelets with travel times for periods of 100s, 10s, and 1s, respectively in seconds.
Figure 6. Reverse cross-correlation results using reference signal for period 1 second.
2.2. Vertical and lateral resolution
Both lateral and vertical resolution are important, using a simple analysis of the relationship between velocity and period we can find the lambda or wavelength in the depth domain and distance. Lateral and horizontal resolutions can be used with the 1/4 lambda approach. Table 1 shows the relationship between velocity, period, lambda, and resolution both vertically and horizontally.

Figure 7. Staked signal all period used as synthetic ambient seismic noise data.
Table 1. The relationship between velocity, periods, lambda, and resolution.

| No | T (s) | Group Vel (m/s) | λ (m) | λ/4 (m) |
|----|-------|-----------------|-------|---------|
| 1  | 0.5   | 275             | 138   | 34      |
| 2  | 1     | 281             | 281   | 70      |
| 3  | 2     | 328             | 656   | 164     |
| 4  | 4     | 482             | 1930  | 482     |
| 5  | 5     | 591             | 2957  | 739     |
| 6  | 6     | 722             | 4331  | 1083    |
| 7  | 8     | 1059            | 8472  | 2118    |
| 8  | 10    | 1579            | 15788 | 3947    |
| 9  | 15    | 3052            | 45756 | 11439   |
| 10 | 20    | 3448            | 68952 | 17238   |
| 11 | 30    | 3667            | 110106| 27527   |
| 12 | 40    | 3748            | 149927| 37482   |
| 13 | 50    | 3792            | 189611| 47403   |
| 14 | 100   | 3872            | 387186| 96796   |

3. Result
Based on the results of the dispersion curve synthetic modelling, it can be seen that the value of the surface wave group velocity varies according to the period, in a short period it gives a lower group velocity value than in the long period, the change in surface wave group velocity is significant for more than 10 seconds. Group velocity for each period using the mat_disperse algorithm can provide good information about subsurface conditions. Based on the analysis of the group velocity gradient as a function of the existing model, the effective period that provides good information is at 10 seconds, because the larger the 10 s gradient the group velocity is smaller than the 10 second period. The travel time for surface wave variations depends on the period, from the closest to the farthest distance for a period of 0.5 seconds from 0 to 109 seconds while in a 100 second period the travel time ranges from 0 to 8 seconds. The wavelet convolution approach with travel time can be used as a model of surface wave arrival time forwarding, which is a green function approach in processing ambient seismic noise data. The reverse cross-correlation method from the modeling results is promising in the process of producing the desired signal or synthetic data as if it were the result of field recording. Besides the reverse cross-correlation method as an effort to restore the green function, it seems that approaches with reverse deconvolution and reverse cross-coherence should be tried to produce the desired signal in synthetic data modeling. Based on the existing geological model and the maximum station distance of 30 km, the 30 second period becomes the maximum period that can best describe the arrival time of the surface waves from the convolution results with wavelets. A simple approach using the 1/4 wavelength function can direct us in determining survey designs such as the distance between recording stations that can be adjusted to the target depth, as well as determining the maximum period in the extraction of the green function when processing ambient seismic noise data.
4. Conclusion
The estimate target depth, vertical and lateral resolution depend on the recorded data periods and subsurface velocity model. Effective spacing between stations is strongly influenced by target depth, resolution, data period, and velocity value. Synthetic data modeling or forward modeling can be used as a basis in determining the acquisition design so that data can be recorded optimally in the field.

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