The Study of Automatic Picking of P and S Wave Arrival and Identification of Earthquake Sequence Pattern using Scalogram in Obspy (Python)

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Abstract. Initial identification on an earthquake record (seismogram) is something that needs to be done precisely and accurately. Moreover, the discovery of a series of unexpected successive earthquake events has caused unpreparedness for the community and related agencies in tackling these events. Determining the arrival time of the P and S waves becomes an important parameter to finding the location of the earthquake source (hypocenter) as well as further information related to the earthquake event. However, manual steps that are currently often used are considered to be less effective, because it requires a lot of time in the process. Continuous Wavelet Transform (CWT) analysis can be a solution for this problem. With further CWT analysis in the form of a scalogram, can help to determine the arrival time of P and S waves automatically (automatic picking) becomes simpler. In addition, further CWT analysis can also be utilized to help identify the sequence of earthquake events (foreshock, mainshock, aftershock) through the resulting scalogram pattern.

Keywords: aftershock, CWT, foreshock, mainshock, scalogram, seismogram.

1. Introduction
Geographically, Indonesia is locating between three major plates of the world, including the Eurasian Plate, Pacific Plate, and Australian Plate (Figure 1). Each tectonic plate interacted with each other and resulted in earthquake sources, such as faults and subduction. Therefore, it was not surprising that Indonesia was called one of the most vulnerable countries to natural disasters, especially earthquakes. Constraints that must be faced until now, namely not yet predict when the earthquake occurred, still found difficulties in determining the location of the earthquake source (hypocenter) and the difficulty of distinguishing the pattern of earthquake events. At present, to find out information about earthquakes, specifically regarding the time of an earthquake, it is solved using statistical methods. Manual steps were still often used to determine the arrival time of P and S waves as important parameters to determine earthquake hypocenter [8].

However, with various approaches that have been made to be able to speed up the process of determining the arrival time of P and S waves is still considered ineffective and still requires a long time in its completion. Therefore, to speed up the process can be done using the automatic picking method. Automatic picking analysis using the Continuous Wavelet Transform (CWT) method can be used as a solution to accelerate and simplify the process of determining the phase of the wave [3] [10]. Further CWT analysis in the form of scalogram can also be used to help identify the sequence of earthquake events (foreshock, mainshock, aftershock) through the resulting scalogram pattern.
2. Data and Methodology

Seismic waves are waves that arise due to the release of energy that comes from artificial and natural seismic sources [2] [5]. Seismic waves will be recorded by the seismometer as a seismogram and basically carry information about the seismic source and the medium through which it passes in a function of time or speed with a certain time [1].

A scalogram is a time-scale picture of a signal that is represented in a certain color. The scalogram does not allow for direct interpretation of the frequency, because the scale on the scalogram represents the frequency range and is not a single frequency. To get a scalogram done using the CWT method.

CWT is defined as the sum of the signals $f(t)$ where the multiplier parameter is a scale which is a shifting position and wavelet function ($\omega$) [7].

$$C(\text{scale}, \text{position}) = \int_{-\infty}^{\infty} f(t) \psi(\text{scale}, \text{position}, t) dt$$  \hspace{1cm} (1)

The result of CWT is wavelet $C$ coefficient which is a function of scale and position. Multiplication of each coefficient with the right scale and position will produce a constituent wavelet from the original signal. Wavelets are defined as functions $\psi(t) \in L^2(\mathbb{R})$ with zero-mean, localized in time and frequency.

Through dilation and translation wavelet $\psi(t)$ produces the wavelet family as follows:

$$\psi_a \cdot b(t) = \frac{1}{\sqrt{|a|}} \psi \left( \frac{t-b}{a} \right)$$ \hspace{1cm} (2)

Where $a, b \in \mathbb{R}$ and $a \neq 0$. $a$ is a scale parameter and $b$ is a shift (position) parameter. CWT is defined as the origin product of the wavelet family $\psi \cdot ab(t)$ with the signal $f(t)$ given by the equation:

$$F_w(a, b) = (f(t), \psi a, b) = \int_{-\infty}^{\infty} f(t) \frac{1}{\sqrt{|a|}} \psi^* \left( \frac{t-b}{a} \right) dt$$ \hspace{1cm} (3)

Where $\psi^*$ is the conjugate complex of $\psi$. $F_w(a, b)$ is a time-scale map (scalogram). The flow chart in this study can be shown in the figure below (Figure 2):
The data used in this study is in the form of raw earthquake record data (seismogram) that occurred in Indonesia with varying magnitude. Obtaining the data by downloading through the IRIS [6]. Then the data is analyzed from the initial earthquake event, to the CWT analysis to get a scalogram profile. This process is entirely carried out in Python Software by utilizing the Obspy library/application/module. The use of Python was chosen because it is able to execute large data quickly, its programming language is easy to understand, has a complete module to support research in the field of science, opensource so that it can be used by anyone, and also effective because it can be connected directly to the internet [9].

3. Results and Discussion

This study takes several examples of raw data on earthquake events in Indonesia, which have been downloaded on the IRIS [6]. The series of earthquakes included foreshock, mainshock, and aftershock earthquakes that occurred in Lombok in 2018, North Sumatra in 2017, and Palu in 2018. The CWT analysis is performed to obtain the scalogram results. Foreshock earthquake is an earthquake that occurred before the main earthquake occurred. Foreshock earthquake data used in this study are Lombok earthquake on 28 July 2018, North Sumatra earthquake on 6 January 2017, and Palu earthquake on 28 September 2018. Based on Figure 3 (a) (b) (c) it can be seen that the time of P wave arrival and S is characterized by a color enhancement on the scalogram (red line). P waves always arrive the first time compared to other waves because the speed possessed by the P wave is greater, so the P wave requires a shorter time to reach the recording station than the other waves. The time of arrival of P and S waves in a further foreshock earthquake can be seen in Table 1.

| Earthquake Occurrence       | Tp (second) | Ts (second) |
|-----------------------------|-------------|-------------|
| Lombok, 28 July 2018 (M6.4) | 67.18       | 551.11      |
| North Sumatra, 6 January 2017 (M5.4) | 15.59      | 112.12      |
| Palu, 28 September 2018 (M6.1) | 87.72       | 592.16      |

Identification of earthquake patterns can be seen through the pattern on the scalogram. Figure 3 (a) (b) (c) are successively a foreshock earthquake from the Lombok earthquake on July 28, 2018, North Sumatra earthquake on January 6, 2017, and Palu earthquake on September 28, 2018, scalogram patterns
are relatively more tenuous (wide) and also collect (black circle). In addition, the color on the scalogram for the foreshock earthquake is not too strong and the surface wave duration is not too long.

Figure 3. Lombok earthquake recording and scalogram on July 28, 2018 (a), North Sumatra on January 6, 2017 (b), and Palu on September 28, 2018 (c).

The mainshock earthquake is an earthquake that was present after the foreshock earthquake occurred. Foreshock earthquake data used in this study are Lombok earthquake data on 5 August 2018, North Sumatra earthquake on 16 January 2017, and Palu earthquake on 28 September 2018. Based on Figure 4 (a) (b) (c) it can be seen that the time of P wave arrival and S is characterized by a color enhancement on the scalogram (red line). The time of arrival of P and S waves in the mainshock earthquake can be seen in Table 2.

Table 2. When the P and S waves arrived at the mainshock earthquake.

| Earthquake Occurrence            | Tp (second) | Ts (second) |
|----------------------------------|-------------|-------------|
| Lombok, 5 August 2018 (M6.9)     | 82.16       | 587.07      |
| North Sumatra, January 16, 2017 (M5.6) | 21.55       | 192.12      |
| Palu, 28 September 2018 (M7.5)   | 61.83       | 672.98      |

Identification of earthquake patterns can be seen through the pattern on the scalogram. Figure 4 (a) (b) (c) are respectively the mainshock earthquake from the Lombok earthquake on August 5, 2018, the North Sumatra earthquake on January 16, 2017, and the Palu earthquake on September 28, 2018, a scalogram pattern shows a much stronger and wider color (black circle), then followed by a weakening and reinforcement that ensues (arrow). In addition, it can be observed that the duration at the surface wave is longer.
Aftershock earthquake is small earthquakes that are present after the main earthquake occurred. Aftershock earthquake data used in this study are Lombok earthquake data on 5 August 2018, North Sumatra earthquake on 23 January 2017, and Palu earthquake on 28 September 2018. Based on Figure 5 (a) (b) (c) it can be seen that the time of P and S waves arrives marked by the strengthening of the color on the scalogram (red line). The time of arrival of P and S waves in the aftershock earthquake can be seen in Table 3.

Table 3. When the aftershock earthquake P and S waves arrive.

| Earthquake Occurrence          | Tp (second) | Ts (second) |
|-------------------------------|-------------|-------------|
| Lombok, 5 August 2018 (M4.6)  | 34.99       | 262.55      |
| North Sumatra, January 16, 2017 (M4.9) | 122.06 | 676.03      |
| Palu, 28 September 2018 (M5.0) | 16.41       | 632.18      |

Identification of earthquake patterns can be seen through the pattern on the scalogram. Figure 5 (a) (b) (c) is an aftershock earthquake from the Lombok earthquake on August 5, 2018, North Sumatra earthquake on January 23, 2017, and Palu earthquake on September 28, 2018, the scalogram color on the surface wave is not too strong and tends to be denser (narrower) compared to foreshock and mainshock (black circle) events.
4. Conclusions
Based on the results of the scalogram profile in several cases of earthquake data, it is known that CWT analysis through a scalogram can be used to map the arrival time of P and S waves (wave phase) on seismograms in a simpler, clearer, and faster manner (for recording earthquake events recorded with good). In addition, this technique can also be used to help differentiate earthquake sequence patterns by looking at patterns on the resulting scalogram.

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