3D Seismic Waves Velocity Structure of West Sumatera Seismic Waves Using Earthquake Data from January 2010-December 2017

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Abstract. This study analyses the P wave velocity (Vp) and Vp/Vs based on 3D seismic tomography in West Sumatra. Seismic tomography is a method of reconstructing the image of the subsurface structure of the earth using travel time data. This research uses secondary data obtained from the Incorporated Research Institutions for Seismology (IRIS) from January 2010 to December 2017. The data obtained were 472 earthquake events and 21 seismic stations that recorded the earthquake events. This research consists of the hypocenter relocation, which will simultaneously renew the 1D velocity model using VELEST software, and tomographic inversion using SIMULPS12 software. The minimum anomaly of Vp/Vs value is around 1.39, while the maximum anomaly Vp/Vs value is around 2.05. The Vp distribution results have low and high Vp/Vs values around Sumatra Fault Zone and Mentawai Fault Zone. Anomaly results from the tomogram of these areas have an association with saturated pressure sedimentary areas and the presence of fractures which will further contribute to earthquake events.

Keywords: seismic tomography, Vp, Vp/Vs

1. Introduction
Indonesia is an archipelago located on the confluence of four plates, namely Eurasian, Indo-Australian, Pacific, and the Philippine Sea[1]. The convergence of these plates resulted in the formation of complex tectonic arrangements, such as the formation of archipelago arcs with oceanic trenches, non-volcanic arcs composed of accretionary prisms, volcanic arcs, and back-arc basins[2]. The friction between the plates causes the release of energy, where this energy causes an elastic wave effect so that vibrations can be felt on the surface or are called earthquakes.
One of the regions near the plate convergence zone has a complex geological structure in West Sumatra. This area has a high potential for earthquake hazards. Apart from the subduction area between the Indo-Australian and Eurasian tectonic plates, there are two active faults: the Mentawai Fault Zone (MFZ) and the Sumatra Fault Zone (SFZ). This is evidenced by several earthquakes that damaged this area, including the 2007 Padang Panjang earthquake with Mw 6.4 and 6.3, the Pariaman earthquake in 2009 Mw 7.9, and the Pagai Selatan earthquake in the Mentawai Islands in 2010 with Mw 7.2.

These events caused damage and casualties. Optimal mitigation efforts need to be done to minimize the impact of the disaster that occurs. Efforts can be made to identify active seismic zones by using the imaging method of subsurface structures. One of these methods is seismic tomography, and this method reconstructs the subsurface structure of the earth using travel time data. In theory, the seismic tomography will present an image of the earth's subsurface in the velocity domain[3].

2. Data and Methodology
The data in this study was used from the Incorporated Research Institutions for Seismology (IRIS) from January 2010 to December 2017. The data obtained is an earthquake catalog which contains information about the time of the earthquake, time of origin, arrival time of P and S waves, earthquake hypocenter earthquake (latitude, longitude, and depth), 1D seismic wave velocity model, and observation station data.

The data used for the computation of tomographic inversion were 295 events with 21 recording stations. The data used are earthquake event data with a minimum number of recording stations of 4 stations and azimuth GAP value <220°. Furthermore, model parameterization is carried out by determining the grid with an area of 1000 km×1000 km and a depth of 70 km, the model was built with dimensions of 11×11×7 blocks, as shown in Figure 1. The initial velocity model used in the tomographic inversion process is shown in Table 1. The distribution of the seismic station density, the position of the epicenter, and the target area of the study are the primary consideration factor determining the grid size in the area.

| Depth (km) | Velocity (km/s) |
|------------|-----------------|
| 0          | 5.53            |
| 20         | 6.86            |
| 27.5       | 7.74            |
| 35         | 8.04            |
| 50         | 8.15            |
| 70         | 8.23            |
In this study, a damping test was carried out using a trade-off curve analysis to obtain the optimum damping value. In this study, Vp's optimum damping value was 40 shown in Figure 2.a, and Vp/Vs was 85 in Figure 2.b.

After the tomographic inversion stage, a resolution test is carried out, aiming to see the resulting resolution, and is carried out before the interpretation of the tomogram. In this study, two resolution testing methods were carried out, namely the Checkboard Resolution Test (CRT) and the Derivative Weight Sum (DWS). The CRT model is tested using the forward modeling method. If the results obtained from the CRT process are the same or close to the initial model, the tomographic inversion results have a good resolution. Furthermore, DWS helps test the resolution of the tomographic results based on each node's ray distribution.
3. Results and Discussion

3.1 Hypocenter Relocation

As a validation of the hypocenter relocation study, a comparison between the residual values' frequency before and after the hypocenter relocation was made in Figure 3. This validation was carried out to test the relocation results' accuracy, and the relocation results were said to be good if the residual time value was close to zero. The residual RMS value obtained after relocating was smaller than before the relocation. This is because the velocity model used is a 3D velocity model so that the relocation results obtained are better as shown in Figure 4.

![Figure 3. Histogram RMS error, where orange color is the result of VELEST software and blue color is the result of relocation with SIMULPS12 software](image)

![Figure 4. The result after relocation using SIMULPS12](image)
3.2 Resolution Test and Seismic Tomographic Image

The difference in quality and amount of arrival time data between Vp and Vs will result in different artifacts on each model. To avoid this, Vp is modeled directly from the arrival time of P-wave, but for Vs model is calculated by inversion of Vp/Vs with Ts-Tp data[6]. So the resolution test is done on the inversion results of Vp and Vp/Vs tomography.

As can be seen in Figure 5.a and Figure 6.a are DWS Vp's results, the blocks that have good resolution are those that pass a lot of rays marked with gray blocks. In this study, the minimum DWS Vp score is 0, and the maximum value of 12,665. In this study, an average DWS Vp score of 400 was obtained, so a DWS value greater than 400 is chosen to limit the area where a lot of light passes so that changes are visible, which are marked with dotted black lines. Figure 5.b and Figure 6.b are a resolution test with CRT Vp which shows well-resolution blocks seen in the checkerboard models, namely horizontal slices with a depth of 20, 30, and 50 km marked with a dotted black line. Figure 5.c and Figure 6.c are the result of tomography inversion, high-velocity anomalies are characterized by blue gradations with tomographic results ranging from +5% to +10%, which are relatively high compared to the surroundings. In comparison, low-velocity anomalies are characterized by red gradations ranging from -5% to -10%, which are lower than the surrounding area.

Similar to the P wave, the Vp/Vs also get the results of the resolution test shown in Figure 7.a and Figure 8.a. This study obtained a minimum and a maximum Vp/Vs DWS of 0 and 1,172. The average Vp/Vs DWS value of 125, so a value greater than 125 is chosen to limit the area where a lot of light passes so that changes are visible, which are marked with black dotted lines. Figure 7.b and Figure 8.b are a resolution test result with Vp/Vs CRT showing well-resolution blocks seen in reconstructed areas such as chessboard models, i.e. horizontal slices with depths of 20, 30, and 50 km. There is little difference between resolution test results on Vp and Vp/Vs, where P wave CRT results show better chessboard patterns. This can be due to the data quality and the number of more P wave phases used in the tomography inversion process. Figure 7.c and Figure 8.c are the result of Vp/Vs. The initial Vp/Vs model used in this study was 1.73. In this study, the minimum and maximum Vp/Vs were 1.39 and 2.05.

Dark blue gradations show maximum positive velocity anomalies, while deep red indicates maximum negative velocity anomalies. The positive velocity anomaly suggests that the resulting velocity is greater than that of the initial model velocity in the area and indicates harder and denser rocks in the area. Negative velocity anomalies indicate that the resulting velocity is smaller than the average velocity of the site. The lower P wave velocity value observed in rocks with high porosity and the presence of boulders will also reduce seismic velocity compared to intact rock[5].
Figure 5. Horizontal slice tomogram $V_p$ ($Z=0$ km, 10 km, 20 km). a). Derivative Weight Sum (DWS), b). Checkerboard Resolution Test (CRT), and c). Seismic tomography inversion. The yellow triangle is an earthquake recorder station, a thick green line is a fault, a thick black line is a trench, a dotted black line is an area that has a fair resolution, a dotted green line is an interpretational area, and a white circle is a hypocenter position.
Figure 6. Horizontal slice tomogram $V_p$ ($Z=30$ km and 50 km). a). Derivative Weight Sum (DWS), b). Checkerboard Resolution Test (CRT), and c). Seismic tomography inversion. The yellow triangle is an earthquake recorder station, a thick green line is a fault, a thick black line is a trench, a dotted black line is an area that has a fair resolution, a dotted green line is an interpretational area, and a white circle is a hypocenter position.
Figure 7. Horizontal slice tomogram $V_p/V_s$ ($Z=0$ km, 10 km, and 20 km). a). Derivative Weight Sum (DWS), b). Checkerboard Resolution Test (CRT), and c). Seismic tomography inversion. The yellow triangle is an earthquake recorder station, a thick green line is a fault, a thick black line is a trench, a dotted black line is an area that has a fair resolution, a dotted green line is an interpretational area, and a white circle is a hypocenter position.
Figure 8. Horizontal slice tomogram Vp/Vs (Z=30 km and 50 km). a). Derivative Weight Sum (DWS), b). Checkerboard Resolution Test (CRT), and c). Seismic tomography inversion. The yellow triangle is an earthquake recorder station, a thick green line is a fault, a thick black line is a trench, a dotted black line is an area that has a fair resolution, a dotted green line is an interpretational area, and a white circle is a hypocenter position.

In general, horizontal slices on tomograms with a depth of 20 km are seen that the earthquake event is in the forearc area and Mentawai fault zone. This area appears to have a low P wave velocity anomaly except in the Pulau Batu. Simultaneously, for Vp/Vs tomograms, it is obtained a relatively high Vp/Vs value (1.73–2.05). Also, along the Sumatra Fault Zone area is seen to have a low P wave velocity anomaly characterized by a red anomaly. However, the Vp/Vs tomogram results have a high Vp/Vs value in the Siulak segment, Dikit segment, and Ketaun segment. This can identify that the third area of the segment is an area of high porosity. At the same time, the Sianok segment has a low Vp/Vs value (1.29-1.73). This indicates that this area has hard rocks and is denser than the surrounding area.

At a horizontal slice with a depth of 30 km, the Sumatra Fault Zone area has a low Vp anomaly and high Vp/Vs value. Mentawai Fault Zone has a low Vp anomaly, and the Vp/Vs tomogram result obtained a relatively high Vp/Vs value. Tomogram results at 50 km are seen that in Sumatra Fault Zone area has low Vp anomalies except in Ketaun segment while obtained low Vp/Vs value. There are also differences in Vp and Vp/Vs anomalies in Siberut island areas where Vp is high while the Vp/Vs value is low. Areas in the forearc were observed to have low Vp values and high Vp/Vs values were interpreted as fracture areas or sediment pressure saturated. In general, the research results are shown in Table 2.
Table 2. Catalog of interpretations

| Vp  | Vp/Vs | Interpretation                                                   |
|-----|-------|-----------------------------------------------------------------|
| Low | High  | Presence of damage or saturated pressurized sedimentary areas  |
| Low | Low   | The presence of weak areas such as faults or sub-surface structures resulting from tectonic activity |
| High| Low   | The conduit of magma intrusion or hard rock area                |

4. Conclusion

The result is there are variations of Vp and Vp/Vs anomalies distribution around the Sumatra Fault Zone and Mentawai Fault Zone. The low Vp anomaly and high Vp/Vs value are associated with high porosity and fractures areas. In the horizontal slice (Z=50 km), the Mentawai Fault Zone has a high Vp and low Vp/Vs values are areas harder and denser than the surrounding rocks. Whereas areas that have low Vp and Vp/Vs values are fracturing areas. The areas are associated with saturated pressure will affect the pore pressure, which will contribute to earthquakes.

Some parts of the study area cannot be interpreted because of the lack of earthquake events and uneven station distribution. Vs also have less resolution because the S-phase number is minimal, making Vp/Vs interpretation more difficult. For further study, the S-phase should be re-picked to get more reliable data.

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