Comparison Study of Crustal Structure in Aceh Region based on Volcanic Arc System using Receiver Function Method

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Abstract. Aceh region has a very complex crustal structure from the forearc ridge to the backarc basin. This study aims to determine the velocity model of P and S waves and the depth of Moho discontinuity. This research was conducted using teleseismic earthquake data (30°-90° from the station) with M>6 from four seismic stations belonging to the BMKG in Aceh region. The stations are qualified based on the volcanic arc system zone. Furthermore, the velocity model determined by result of forward modelling, while the depth of the Moho layer estimated by migrated receiver function from time domain to the depth domain. At station SNSI that represented the forearc ridge zone, the depth of Moho is ±28 km, at station TPTI represent the forearc basin is ±16 km, while at zone with higher topography, namely volcanic arc zone represented by station KCSI, the Moho depth was identified at ±38 km, and the backarc basin represented by station LASI with ±40 km depth of Moho. This variation occurs because the composition of the earth's layers below the station is diverse also different topography for each station.

1. Introduction
Aceh region is located at the northern tip of Sumatra Island and it has characteristics of a tectonic structure that is generally the same as other regions in Sumatra. One of tectonic feature which is a continuation fault from the southward is the Great Sumatran Fault (GSF) lineament which plays an important role in the number of seismicity in the Aceh region. The lineage of the Sumatran Fault in Aceh Province is divided into 3 segments, namely the Tripa Segment, the Aceh Segment, and the Seulimeum segment. These segments stretch from 120 to 200 km with significant seismicity in the past [1] and active until today. In addition, the Sumatra region in western Indonesia is considered part of the Sunda Arc, which results from the confluence of the Indo-Australian and Eurasian Plates [2]. Plate subduction in the southwest of Aceh also plays a very important role in the formation of tectonic system and seismic activity in the Aceh area, including the potential to cause tsunamis. According to two complex geological conditions, Aceh Province is one of the areas with high seismic activity in Indonesia.

Because of the influence of high seismic activity, it is deemed necessary to take a deeper look at the structure of the subsurface crust, in the form of slabs, the depth of the Moho discontinuity, and the determination of the velocity profile in order to understand the geodynamic mechanism of plate movement that occurs under the earth's surface in the Aceh region. This can be reviewed through the receiver function method. This method uses a teleseismic signal as input data which will then be
processed with a radial or transverse component deconvolution technique from a vertical component seismogram consisting of P-to-S conversion waves from various layers below the seismic station [3].

Research using this method was first applied by Langston [4] to describe the subsurface structure of Mount Reiner with teleseismic data recorded at the LON Longmire station, Washington. This research was conducted by rotating the wave vector horizontally after applying the deconvolution technique to eliminate the function of time and instrument response. The deconvolution technique is applied because the seismogram used is earthquake data from various depths. Furthermore, Macpherson conducted research in the Sumatra region [5]. This study estimates the speed structure under GE network seismic stations and several broadband seismic stations, namely LHMI, GSI, BKNI, and MNAI stations. Time domain iterative deconvolution is used in this study to minimize the noise present in the waves. The average Moho depth around the island of Sumatra is obtained using a linear inversion technique. From this study, the results obtained with a significant difference from the CRUST2.0 speed model. This difference is considered a representation of the diversity of the geological environment of the station used, so the results of this study have a more detailed value.

Beside these two studies, a similar study conducted in Indonesia identified layers of the Earth's crust in the Simeuleu area using the combined inversion of the receiver and surface wave dispersion functions with this method and found a change in velocity associated with the subduction of the Indo-Australian Plate [6]. In addition, in the Simeuleu area, research using the tomography method was also carried out which resulted in a velocity model showing the intermediate velocity anomaly zone between the oceanic crust related to the uplifted topography above the oceanic crust [7].

2. Method

This study was conducted using teleseismic earthquake data with the provisions of the earthquake distance of 30°-90° from the station location and magnitude of more than 6 (M>6) from 4 seismic stations belonging to the BMKG (Agency for Meteorology, Climatology and Geophysics) which are qualified in the Aceh region. The stations used are based on the volcanic arc zone of the Aceh region, namely the forearc ridge zone represented by the SNSI station, the forearc basin zone represented by the TPTI station, the volcanic arc zone represented by the KCSI station, and the backarc zone represented by the LASI station as can be seen in Figure 1.

![Figure 1](image.png)

Figure 1. (a) Distribution of stations used and (b) Distribution of used teleseismic earthquakes (BMKG)

The receiver function method utilizes the propagation of body waves in distant earthquake events received by the receiving station by eliminating the source time and instrument response functions from the seismogram at the receiving station. The P wave that strikes an inclined object at the discontinuity boundary is refracted as a P wave and partly converted into an S wave and several other
conversion wave phases which will later provide information about the depth of the discontinuity boundary and impedance contrast [8] as can be seen in Figure 2.

Figure 2. Receiver function diagram [8]

Qualification of teleseismic earthquake data is based on a fairly high and intact SNR (signal to noise ratio). Furthermore, the appropriate waveform needs to be recorrected using the CPS (Computer Program for Seismology) program. Seismic waves recorded in broadband seismometers are composite waves generated by many events; multi-path propagation, conversion, and splitting of waves on the earth which are heterogeneous and laterally anisotropic [9] and recorded in ZNE coordinates (vertical, north-south, east-west). Therefore, it is necessary to make corrections in the form of rotation of the seismogram components from ZNE coordinates (vertical, north-south, east-west) to ZRT coordinates (vertical, radial, transverse). The horizontal component of the original signal from the seismometer is rotated to the radial and transverse coordinates to match the direction of the earthquake wave propagation [10]. Furthermore, the correction process is continued with the deconvolution method which aims to eliminate the effect of the earthquake source so that only the receiving function is obtained. This stage is carried out on the radial component which is carried out repeatedly (iteratively) [11] until the best value is obtained (fit 90 %). In addition, at this stage filtering is also carried out to remove noise using a Gaussian filter with a width of $a = 1.5$ which can filter noise with a frequency $> 0.75$ Hz. In this study, the determination of the depth of the Moho layer was carried out based on the output of the inversion process through forward modelling [12] and was strengthened through the migration output of the receiver function [13]. In addition, through the output of the inversion results can also determined local velocity variations under the observation station. The formulation used in the inversion process is Equation (1).

$$y = F[x]$$

where $y$ is the data from the observation that the receiver function has not been updated and $x$ is the wave velocity vector. Next, Equation (1) is iteratively linearized to Equations (2) and (3).

$$\delta y = \nabla F|_{x_n} \cdot \delta X_n$$

$$x_{n+1} = x_n + \delta X_n$$

where $\delta X_n = x - x_n$ is the model correction vector and $\delta y = y - F[x_n]$ is the residual data vector [14], and in the iterative calculation $x_0$ using the AK135 global velocity model.

3. Results and Discussion

In this study, the output of the processing results is presented in the form of velocity profiles of P and S waves and the migration of the velocity model into the depth domain. The results of this processing have been arranged based on the division of the Volcanic Arc System group for each station.

3.1. SNSI Station

At the SNSI station which represents the forearc ridge zone, a Gaussian filter width of 5.0 is used because it is considered to be able for interpret the subsurface layer. At this station, 9 signals of the receiver function were obtained which were then performed inversion of forward modeling and migration to determine the depth of the Moho layer. Through the forward inversion modeling process,
the fitting value between the inversion signal and the observation signal is 96.83 % as can be seen in Figure 3(c). In the P wave velocity model and the S wave velocity model at SNSI stations, it is found that there is a significant variation in velocity wave. The variation of the P wave velocity profile is seen from ~3.4–8.8 km/s from the surface to a depth of 100 km, while the variation of the S wave velocity shown is from ~1.8–4.9 km/s from the surface to depth of ~100 km, as can be seen in Figures 3(a) and 3(b). Furthermore, from this velocity profile, it is observed that there is a significant increase in velocity and it is suspected that the Moho discontinuity layer is at depth of about 24 km. This is reinforced by the migration output (Figure 3(d)) which shows a significant Ps phase at a depth of about 28 km below the top slab of the Indo-Australian continental plate subducting beneath the Eurasian continental plate.

![Figure 3](image)

**Figure 3.** (a) P wave velocity profile, (b) S wave velocity profile, (c) Fitting value, and (d) Receiver function migration on SNSI Station

### 3.2. TPTI Station

The TPTI station in this case represents the forearc basin zone with 21 receiver function signals originating from various back-azimuths. Through the inversion process, the fitting value between the inversion signal and the observation signal is 96.03 % as can be seen in Figure 4(c). In the P-wave and S-wave velocity models of the TPTI station, it is found that there is a significant variation in wave
speed. The variation of the P wave velocity profile at the TPTI station is seen at ~5.6-9.6 km/s from the surface to a depth of 100 km, while the variation of the S wave velocity shown is from ~3.1-5.2 km/s from the surface to a depth of ~100 km, as can be seen in Figures 4(a) and 4(b). From these two velocity profiles, it can also be seen that there is a significant increase in velocity which can be considered as a change in the Moho discontinuity layer, which is at a depth of about 16-24 km. This is consistent with the migration output which shows a significant Ps phase suspected to be the Moho layer at a depth of ~16 km as shown in Figure 4(d).

![Image](image_url)

Figure 4. (a) P wave velocity profile, (b) S wave velocity profile, (c) Fitting value, and (d) Receiver function migration on TPTI Station

### 3.3. KCSI Station

At the KCSI station which represents the volcanic arc zone, there are 30 receiver functions with fitting value between the inversion signal and the observation signal of about 97.90 % as can be seen in Figure 5(c). The variation of the P wave velocity profile at the KCSI station starts from ~4.4-10.3 km/s from the surface to a depth of 100 km, while the variation of the S wave velocity shown starts from ~2.5-5.6 km/s from the surface to a depth of 100 km, as can be seen in Figures 5(a) and 5(b). The Moho depth of these two velocity profiles can be observed at a depth of 34-38 km. Reinforced by the migration output which shows the Moho layer is at a depth of ~40 km as shown in Figure 5(d).
In the back arc basin zone represented by the LASI station, 14 receiver function signals were obtained from various back-azimuths. Through the inversion process, the fitting value between the inversion signal and the observation signal that does not qualify the data criteria is obtained, which is 76.37% as can be seen in Figure 6(c). The lack of fitting values in this zone is thought to be the result of the layer below the station which is composed of thick sediment. In the P-wave and S-wave velocity models at the LASI station, it was found that there was a significant variation in velocity wave. The variation of the P wave velocity profile at the LASI station is seen at ~1.6-9.2 km/s from the surface to a depth of 100 km, while the variation of the S-wave velocity is shown from ~0.9-5.4 km/s from the surface to a depth of ~100 km, as can be seen in Figures 6(a) and 6(b). Through this velocity profile, it is observed that there is a significant increase in velocity which is considered a change in the Moho discontinuity layer, which is at a depth of 42-46 km. Then, based on the migration output, it is shown that the Moho layer is at a depth of about 40 km as shown in Figure 6(d).
Figure 6. (a) P wave velocity profile, (b) S wave velocity profile, (c) Fitting value, and (d) Receiver function migration on LASI Station

From four stations that have been processed, the receiver function provides the Moho depth value and the velocity model with varying results. The recapitulation of the Moho depth and the values of $V_p$ and $V_s$ are summarized in the Table 1.

| Station          | Zone          | RF Sensor | Elevation (m) | RF Signal | Moho Depth (km) | $V_p$ (km/s) | $V_s$ (km/s) |
|------------------|---------------|-----------|---------------|-----------|-----------------|--------------|--------------|
| Forearc ridge    | SNSI          | 14.5      | 9             |           | 28 ± 2          | 8.37         | 4.67         |
| Forearc basin    | TPTI          | 9.0       | 21            |           | 16 ± 2          | 7.03         | 3.92         |
| Volcanic arc     | KCSI          | 204.7     | 27            |           | 40 ± 2          | 8.12         | 4.53         |
| Back arc basin   | LASI          | 13.0      | 14            |           | 40 ± 2          | 8.36         | 4.66         |
Based on the recapitulation of the values listed in Table 1, in the forearc ridge zone, the Moho depth value is around 28 ± 2 km. This is supported by the subduction scheme of Singh et al [15], where the Moho oceanic below the Simeulue plateau is at a depth of about 25-28 km. Furthermore, at the TPTI station with the station elevation of 9 m above sea level, the depth of the Moho layer is around 16 ± 2 km. This depth value is supported by research by Anggono et al who have researched the receiver function using the H-k stacking method at the TPTI station, where in this study the depth of Moho was about 20 km [16]. This research also supports the results of an observation from volcanic arc zone represented by the KCSI station which states that the depth of Moho is at a depth of about 38 km. Then, in the last zone, namely the backarc basin represented by the LASI station, the Moho depth is found at a depth of 40 ± 2 km. This value was confirmed by the research of Bora et al who measured the receiver function using the Neighbourhood Algorithm (NA) inversion method at three stations located in the backarc basin zone, namely LHMI, PMBI, and BKNI, in which the thickness of the crust is up to 33 ± 2 km as the beginning of Moho layer discontinuity boundary [3]. These four stations are located in four volcanic zones and sequentially have a deeper Moho discontinuity layer associated with an increasing topography.

4. Conclusion
The depth of the Moho layer varies from the forearc ridge to the backarc associated with the topography of the measuring station. Moho's depth ranges from 16-42 km below the surface. From the forearc ridge, the depth of the Moho ranges from 26-30 km. Then, in the forearc basin zone, the Moho depth is around 16-25 km. Then, in the zone with increased station topography, namely the volcanic arc zone, the Moho depth was found to be around 37-40 km. Finally, at stations in the back arc zone, the depth of the Moho layer is deeper, at a depth of 38-40 km.

Local velocity models of P and S waves in the Aceh region also vary based on the volcanic zone. In the forearc ridge zone, the values of \( V_p \) and \( V_s \) are 8.37 km/s and 4.67 km/s, in the forearc basin zone the values of \( V_p \) and \( V_s \) are 7.03 km/s and 3.92 km/s. Furthermore, in the volcanic arc zone, the values of \( V_p \) and \( V_s \) are 8.12 km/s and 4.53 km/s, and in the volcanic backarc zone, \( V_p \) is 8.36 km/s and \( V_s \) is 4.66 km/s.

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