Identification of Crustal Thickness in Central Part of Sumatra Using Teleseismic Receiver Function Method

P Ariyanto¹, M D Atthonthowi¹*, B Pranata², and B S Prayitno²

¹ Program Studi Geofisika, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika, Indonesia
² Badan Meteorologi Klimatologi dan Geofisika, Indonesia

*Email: ditto.atthonthowi@gmail.com

Abstract. The Central part of Sumatra is a region that has a high potential for earthquakes. This research intended to determine the crustal thickness of the earth, P and S wave velocity profiles, and \( \frac{v_p}{v_s} \) value in the Central part of Sumatra using stacking H-k and inversion techniques based on the analysis of receiver function. This study utilized teleseismic earthquake data with a distance of 30⁰ to 90⁰ from the station and magnitude more than 6 (M>6). The stations used in this study were 3 BMKG broadband stations located in 3 zones, the fore arc ridge zone (SISI), the volcanic zone (PLSI) and the back arc zone (TPRI). The crustal thickness varies in the fore arc ridge zone (SISI) estimated 17.8 km, volcanic zone (PLSI) reaches 29.7 km and the back arc zone (TPRI) reaches 34 km. The crustal thickness is quite thick under the PLSI and thicker beneath TPRI station. These possibly due to the effect of topography and isostatic compensation in the station. However, whether there is a correlation between crustal thickness and topography needs further research using more stations. The highest \( \frac{v_p}{v_s} \) value was found in the volcanic zone of 1.9, that might be associated with the presence partial melting beneath the station. Meanwhile, the \( \frac{v_p}{v_s} \) value in the back arc zone is 1.72, indicating a relatively more homogeneous structure.

1. Introduction

The Island of Sumatra is part of the convergence zone between two plates, namely the Eurasian plate and the Indo-Australian plate. The gathering zone between the plates forms a trough known as the collision zone. The trench integrates the northward movement of the Indo-Australian plate against the Eurasian plate. The movement of the Indo-Australian plate and the Eurasian plate in the subduction zone has caused earthquakes [1].

The central part of Sumatra is a continental plate boundary which consists of two fault systems, namely a strike-slip fault system with a dextral orientation and a subduction dip-slip interface which has a greater influence [2]. Central Sumatra is an area that has a high potential for earthquakes and tsunamis. This region has three main sources of active earthquake generators, namely the subduction line (Megathrust), the Mentawai fault and the Sumatran fault. Based on historical records, the central Sumatra region has experienced several destructive earthquakes in 1822, 1835, 1981, 1991, 2005, and 2009 in Padang, 2003 in Agam, 2007 in Bukittinggi, and an earthquake accompanied by a tsunami in 1861 in Mentawai, 1904 in Sori-sori, and in 2010 it happened again in Mentawai [3]. Historically segments in the Sumatra region can generate earthquakes with a magnitude of 7 SR. [4]. Seismicity map in Central Sumatra can be shown in Figure 1.
This research uses the receiver function method to analyze the structure of the earth’s crust in central part of Sumatra. In Indonesia, several studies about crustal structure using receiver function analysis have been carried out by several researcher [5-8]. It is necessary to analyze the structure of the earth’s crust in this area given the high level of vulnerability to earthquakes and tsunamis. The receiver function is a method that can interpret the structure of the earth and its discontinuity plane by utilizing a teleseismic waveform on a three-component seismic sensor. Teleseismic P waves will be converted into S waves in the discontinuity plane below the receiving sensor and the difference in arrival time between the two can be used to determine the crustal thickness [9]. In addition, the local velocity model from the inversion of the receiver function of this study is expected to improve accuracy in determining hypocenters and tsunami early warnings in central part of Sumatra.

2. Method
The data utilized in this research is teleseismic waveform data with a magnitude of more than 6 (M>6) and an epicenter distance of 30° – 90° from the receiver station. This research is located in central Sumatra and the data from this study comes from 3 broadband 3 component seismometer sensors belonging to the Meteorology, Climatology and Geophysics Agency (BMKG). The study area, epicenter of earthquake and the seismic stations used in this study can be shown in Figure 2.
2.1. Receiver function method

The receiver function is a technique used to map the structure of the earth layer underneath the receiver by utilizing teleseismic waves and is a time series that represents the conversion of P to S waves at discontinuities in response to the structure of the earth beneath the receiver. The response comes from the propagation of teleseismic waves that pass through a medium with different characteristics. If the propagation of a body wave such as a P wave passes through a discontinuity plane, then the P wave energy will be divided into several phases such as being transmitted directly to the surface, some of the energy is reflected back, and can be converted into an S wave. The first wave amplitude and clearly visible in the receiving function is a wave P directly and then followed by phase conversion of Ps waves. The distinction in arrival time between the P wave phase and the Ps conversion phase can be utilized to calculate the estimated crustal thickness if the velocity model of the area is identified [10].

\[
R(t) = E_{iR}(t) * Z(t)
\]  

Denoted \( R(t) \) is the signal from the radial component in the time domain, \( E_{iR} \) is the iteratively obtained radial component receiving function model. \( Z(t) \) is the vertical component seismogram and \( * \) is the convolution operator [11].
2.2. Stacking H-k

The aim of stacking H-k is to calculate the estimated crustal thickness (H) and the \( \frac{v_p}{v_s} (k) \) value from the time series of the receiver function. This method calculates the distinction in the propagation time of Ps, PpPs, and PpSs+PsPs waves to direct P waves. Estimation of the crustal thickness is done by stacking the receiver function data in the H-k domain, using the equation.

\[
s (H, k) = w_1 r(t_1) + w_2 r(t_2) - w_3 r(t_3)
\]  

(2)

Denoted \( w \) is the weighting factor provided that \( \Sigma W = 1 \) and \( r \) is the radial receiver function at \( t_1, t_2, \) and \( t_3 \) with \( t \) being the estimated time difference between the arrival times of the Ps, PpPs, and PpSs+PsPs [10].

3. Results and Discussion

In this study, we used 3 stations which represent 3 zones, fore arc ridge zone (SISI), the volcanic zone (PLSI) and the back arc zone (TPRI). The receiver functions generated by each station has a fit >90% of deconvolution.

3.1. Fore Arc Ridge Zone

The teleseismic earthquake data used at this station was recorded from 2018 to 2020 and produced as many as 20 radial component receiving functions as shown in Figure 5. Based on the results that are plotted in quadrant 4 there is no receiver function signal, this is because the data in quadrant 4 does not have good quality so that the receiver function cannot be calculated. A direct P phase or Pp is observed at ~0 s. The Ps phase used to estimate the depth of the moho layer was observed at ~3 s. Furthermore, the PpPs phase can be observed at ~6 s.

![Figure 5. Radial component receiver functions at SISI station based on back azimuth](image)

The P wave velocity profile can be seen in Figure 6. The P wave velocity has a minimum value of 3.06 km/s and a maximum value of 9.81 km/s. The estimation of the crustal thickness is approximately 2,022 km, which is indicated by an increment in the P wave velocity from 6.4 km/s to 6.8 km/s. The S wave velocity at SISI station has a minimum value of 1.7 km/s and a maximum of 5.36 km/s. The crustal thickness is estimated around 20-22 km marked by an increment in the velocity of the S wave from 3.2 km/s to 4 km/s.
Figure 6. P and S wave velocity profiles at SISI station

Figure 7 shows the results of the stacking $H$-$k$ calculation at the SISI station. Based on the results of these calculations, the crustal thickness is 17.8 km and the $v_p/v_s$ value is 1.2. The fore arc ridge zone in Sumatra is a seismic anisotropy zone [12]. The $v_p/v_s$ value generated at SISI station is very small, this is because the use of the stacking $H$-$k$ method to estimate the $v_p/v_s$ value in the anisotropy zone is less accurate [13].

Figure 7. Stacking $H$-$k$ at SISI station

3.2. Volcanic Zone
Based on 22 radial component receiver functions as shown in Figure 8, the direct P phase or Pp is seen at ~0 second and the P wave phase converted to S wave is seen at ~5 second and the PpPs phase is seen at ~13 second.
Figure 8. Radial component receiver functions at PLSI station based on back azimuth

The P wave velocity profile under the PLSI station is shown by Figure 9. The P wave velocity beneath this station has a minimum value of 4.46 km/s and a maximum of 10.4 km/s. The estimation of crustal thickness is approximately 28-32 km, which is indicated by an increment in P wave velocity from 7.2 km/s to 8.4 km/s. The velocity of the S wave at the PLSI station has a minimum value of 2.48 km/s and a maximum of 5.8 km/s. The crustal thickness is estimated around 28-32 km which is indicated by an increment in the velocity of the S wave from 4 km/s to 4.8 km/s.

Figure 9. P and S wave velocity profiles at PLSI station

The estimated crustal thickness obtained based on the calculation of stacking $H-k$ is 29.7 km and the $vp/vs$ value is 1.9. The high $vp/vs$ value at the PLSI station that might be associated with the presence of partial melting so that the S wave velocity when passing through the fluid medium is more attenuated than the P wave. The results of $H-k$ stacking can be seen in Figure 10. This result is in agreement with the receiver function study conducted in the Toba Caldera (volcanic zone) using the PSI station which produced a crustal thickness of 30 km and the $vp/vs$ value was 1.87 [14].
3.3. Back Arc Zone

The receiver function of the radial component generated at the TPRI station is 48 as shown in Figure 11. Based on the stacking results of the receiver function, the resulting phases are quite simple, indicated by the fact that there are only two phases at this station. This condition is appropriate because the TPRI station represents a back arc zone where seismic activity is low in this zone so that the resulting phase is very clear and not complex. The direct P phase or Pp is seen at ~0 s and a P wave phase converted to an S wave is seen at ~4 s.

![Figure 10. Stacking H-k at PLSI station](image)

![Figure 11. Radial component receiver functions at TPRI station based on back azimuth](image)

Figure 12 shows the P wave velocity profile below the TPRI station. The P wave velocity below this station has a minimum value of 6.1 km/s and a maximum of 9.8 km/s. The estimation of crustal thickness is approximately 32-36 km, which is indicated by an increase in the velocity of the P wave from 8 km/s to 8.4 km/s. The velocity profile of the S wave at TPRI station has a minimum value of 3.41 km/s and a maximum of 5.46 km/s. The crustal thickness is estimated around 32-36 km which is indicated by an increase in the velocity of the S wave from 4.4 km/s to 4.8 km/s.
Figure 12. P and S wave velocity profiles at TPRI station

Figure 13 shows the results of the stacking $H$-$k$ calculation at the TPRI station. Based on the results of this calculations, the estimated crustal thickness is 34.1 km and the $vp/vs$ value is 1.72. This result is supported with the study of receiver function by Bora et al. [15] using the inversion Neighborhood Algorithm (NA) method in the back arc zone with a crustal thickness of 27-33 km. Bora et al. used the BKNI and PMBI stations to calculate crustal thickness in the back arc of Sumatra [15].

Figure 13. Stacking $H$-$k$ at TPRI station

4. Conclusion
Analysis of the P and S wave velocity profile and the crustal thickness in central Sumatra has been carried out using the inversion method and stacking $H$-$k$. Based on the results of the receiver function analysis, we estimated the crustal thickness in the fore arc ridge zone (SISI) is around 17.8 km, in the volcanic zone (PLSI) reaches 29.7 km and the back arc zone (TPRI) reaches 34 km. The crustal thickness is quite thick under the PLSI and TPRI station, possibly due to the effect of isostasy in the zone. Stations with high topography may have deeper Moho as an effect of isostatic compensation. The highest $vp/vs$ value was found in the volcanic zone of 1.9, that might be associated with the presence of magmatic material or partial melting beneath the station. Furthermore, the normal $vp/vs$ value in the back arc zone ($vp/vs \sim 1.72$) probably related to the simple and relatively homogeneous structure beneath this station.
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