Crustal thickness estimation in Indonesia using receiver function method

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Abstract. The existence of seismic wave velocity difference in the Earth crust and mantle creates the possibility to use earthquake data for estimating the crustal thickness utilizing the Ps conversion phase in the boundary. The radial component signal was deconvolved from the vertical component in the frequency domain to estimate receiver function for Indonesia region. We implemented the water level deconvolution techniques with a Gaussian filter of 2.5 Hz to eliminate the high frequency noise in the receiver function. The H-k stacking technique was performed to all receiver functions from each event to predict the crustal thickness and the Vp/Vs ratio below the stations. We analyzed ten azimuthally distributed teleseismic earthquakes recorded by 108 stations of BMKG. The result shows that the crustal thickness in Indonesia varies from 20 to 39.9 km. The western part of Sumatera, northern part of Sulawesi Island, and North Maluku region show generally thinner crust with value about 20 to 25 km. The North Sumatera, Central Java, and East Java show a considerably thicker crust of up to 36 km. Furthermore, our result also reveals a difference of crustal thickness about 5 km with the previous studies.

1. Introduction

Earth can be separated into three sections based upon chemical composition: the crust, the mantle, and the core. The crustal thickness varies in each area. The existence of seismic wave velocity difference in the Earth crust and mantle introduces the possibility to use the earthquake data for estimating the crustal thickness. Receiver function method uses Ps conversion phase in the crust-mantle boundary and processes the earthquake data to identify the structure of Earth crust and upper mantle. The crustal thickness studies in some areas in Indonesia have been conducted using this method [1-4]. Limited studies about the crustal thickness of Indonesia encourage us to conduct research covering all areas in Indonesia using greater station number. In this study, we are not only estimating the crustal thickness variation in Indonesia, but also comparing the result with the previous studies.

Information about crustal thickness can support the study of tectonic evolution and geological process in certain area. The Moho discontinuity which separates the crust and mantle is an important parameter for many studies, such as gravity modelling, upper-mantle tomographic studies, location of seismic events, and forward seismic wave propagation [5]. Therefore, this study can be used as supporting data to any researches in the future and also provide additional references for the crustal thickness of Indonesia.
2. Data and Methods
Seismic wave that arrives at seismic station contains information about the seismic source, travel track, and the structure below the station. By eliminating source structure and travel track effect, we obtain the isolated local structure information that is called receiver function. Receiver function method is based upon the fact that the P wave will be refracted not only as P wave but also as S wave when it hits a subsurface boundary (for example The Moho discontinuity). The arrival time and amplitude of P-S converted wave and its reverberation represent the boundary’s position.

In this study, we calculate the receiver function through analyzing teleseismic events recorded on the three-component instrument from 108 stations of BMKG. Ten azimuthally distributed events with magnitude more than 6.5 and distance more than 30° are utilized. Location of stations and teleseismic events utilized in this study are shown in Figure 1.

![Figure 1. Seismic stations and teleseismic earthquakes utilized in this study. Seismic stations are denoted by black dots, teleseismic events used in this study are shown with red stars and the study area is shown in red colour.](image)

To calculate receiver function, first we windowed the teleseismic waveform from 10 seconds before to 30 seconds after P wave arrival. Then the horizontal components were rotated before frequency-domain water level deconvolution [6] was implemented to generate receiver function. The radial component is deconvolved from the vertical component in frequency domain with the water level of 0.1, 0.01, 0.05, 0.001, and 0.005, adjusted to the smallest misfit obtained. To remove high frequency noises in the receiver function, we carried out a Gaussian filter of 2.5 Hz.

We then implemented H-k stacking method [7] to all receiver functions (RFs) obtained from each event. This method is applied to estimate the crustal thickness and the Vp/Vs ratio below each station. The H-k stacking method involves the summation of all RFs amplitude at times in accordance with Ps, PpPs and PpSs+PsPs. The arrival time of Ps converted phase and its multiple we used are obtained by grid search across a range of crustal thickness (H) and the Vp/Vs ratio (k). Predicted H and k value would yield the largest amplitudes summation. In this study, the grid search range was set from 20 to 40 km for crustal thickness and 1.6 to 2.0 for Vp/Vs ratio with interval 0.01. For this H-k stacking method, we assumed that the mean velocity of P-wave is 6.3 km/s, and the value of ray parameter is 0.06 s/km.
3. Result and Discussion

Figure 2 shows observed radial component recorded at PMBI station compared to the calculated radial component which is generated from the convolution of the vertical component with receiver function. Observed radial component and calculated signal are quite similar, which indicate the receiver function generated from water level deconvolution has a good quality. The stacked receiver function and all receiver functions ordered by the back azimuth of 4 stations are shown in Figure 3.

![Figure 2](image)

**Figure 2.** Observed radial component recorded at PMBI station (black line) compared to the calculated signal (red line).

![Figure 3](image)

**Figure 3.** Stacked receiver function (red line) and all receiver functions (black line) ordered by the back azimuth for 4 different stations.

To estimate the thickness of the earth crust (H) and Vp/Vs ratio (k) below each station, we applied H-k stacking method to all receiver functions. Figure 4 shows the H-k stacking results for 4 stations.
Black cross represents the estimated value of H and k. All stacked receiver functions and H-k stacking results for all station can be accessed at bit.ly/hasilRF.

We can see yellow ringing area around black cross in Figure 4, which represents uncertainties in H-k stacking. The uncertainties of H-k stacking could be caused by the mean velocity of P-wave and the value of ray parameter we assumme are not the same as the real condition. If the real value of ray parameter and the mean velocity of P-wave beneath the station are quite close to the value we assume, the ringing structure in H-k stacking could be clear as shown at Station PMBI. Otherwise, some stations exhibit severe ringing which may be caused by the real value of ray parameter are not quite close to 0.06 s/km, and the real velocity of P-wave beneath the station are not quite close to 6.3 km/s.

**Figure 4.** H-k stacked result for 4 different stations. Black cross represents estimated crustal thickness (H) and Vp/Vs ratio (k). Small map shows the location of 4 stations.

We calculate the arrival time of Ps, PpPs and PpSs+PsPs using the estimated value of H and k based on Zhu and Kanamori [7]. Based upon this calculation, we pick the arrival of Ps, PpPs and PpSs+PsPs in the stacked receiver function as shown in Figure 3.

The estimated crustal thickness of each station is then gridded and interpolated to provide an estimate of crustal thickness variation map as shown in Figure 5. The result shows that the crustal thickness in Indonesia varies from 20 to 39.9 km. Some areas in Indonesia have a lower crustal thickness approximately 20 to 25 km which includes the western part of Sumatra, the northern part of Sulawesi...
Island, and also the North Maluku region. Meanwhile, the crustal thickness beneath North Sumatra, Central Java, and East Java is considered as the highest with the value up to 36 km thick.

![Figure 5. Crustal thickness map of Indonesia. The black dot represents seismic stations.](image)

Compared to Goyal’s study [1], our result shows difference ranging from 1 to 4 km for the crustal thickness beneath GSI, LHMI, MNAI, BKNI, and PMBI station. The differences are also found with Syuhada and Anggono’s study [2] at 5 stations located in West Java which are CGJI, CISI, CMJI, CNJI, and SKJI, with a range from 1 to 5 km. In comparison to Syuhada’s study in Nusa Tenggara [3], our result shows a difference by about 1 to 4 km. Wölbner and Rümpker [4] inferred the crustal thickness ranging from 27 to 39 km in Central Java and East Java, whereas we estimated the crustal thickness of 34 to 38 km in the same area. Table 1 summarizes our result compared to the previous studies.

| Station | Crustal thickness in this study (km) | Crustal thickness based on previous studies (km) |
|---------|-------------------------------------|-----------------------------------------------|
| GSI     | 20.39 ± 1.01                        | 19 ± 1 [1]                                    |
| LHMI    | 38.25 ± 0.63                        | 35 ± 1 [1]                                    |
| MNAI    | 27.25 ± 2.29                        | 31 ± 1 [1]                                    |
| BKNI    | 30.65 ± 4.21                        | 27 – 30 ± 1 [1]                               |
| PMBI    | 31.60 ± 1.94                        | 33 ± 1 [1]                                    |
| CGJI    | 37.2 ± 1.3                          | 33.20 ± 1.52 [2]                             |
| CISI    | 31.9 ± 0.7                          | 32.78 ± 2.70 [2]                             |
| CMJI    | 34.5 ± 2.0                          | 39.96 ± 2.30 [2]                             |
| CNJI    | 35.3 ± 1.4                          | 30.03 ± 2.25 [2]                             |
| SKJI    | 33.6 ± 1.1                          | 31.00 ± 1.58 [3]                             |
| SOEI    | 34.67 ± 0.45                        | 37.98 ± 4.11 [3]                             |
| BATI    | 27.28 ± 0.39                        | 28.79 ± 3.04 [3]                             |
| BASI    | 33.73 ± 4.68                        | 34.06 ± 1.51 [3]                             |
| PLAI    | 28.16 ± 1.95                        | 30.81 ± 4.32 [3]                             |
| DBNI    | 28.35 ± 4.07                        | 32.48 ± 4.13 [3]                             |
| MMRI    | 34.67 ± 1.96                        | 37.61 ± 1.90 [3]                             |
| LRTI    | 28.95 ± 0.88                        | 27.33 ± 2.16 [3]                             |
4. Conclusion
We calculated receiver function for 108 stations of BMKG by analyzing 10 teleseismic events. Then we performed the H-k stacking method to all receiver functions to predict the thickness of the earth crust and Vp/Vs ratio beneath each station. Crustal thickness map of Indonesia is then made based on the H-k stacking results. The result shows that the crustal thickness in Indonesia varies from 20 to 39.9 km. The western part of Sumatera, northern part of Sulawesi Island, and North Maluku region show generally lower thickness with value about 20 to 25 km. The North Sumatera, Central Java, and East Java areas have a significantly thicker crust of up to 36 km. Compared to previous studies, our result shows a difference of about 5 km.

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