Crustal structure in the southern part of Central Java based on analysis of tele-seismic receiver function using a neighbourhood algorithm

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Abstract. In this study, we applied receiver functions analysis to determine the crustal thickness, the ratio of Vp/Vs and the S wave velocity in the southern part of the Central Java. We selected tele-seismic data with magnitude more than 6 (M>6) and epicenter distance 30°-90° recorded from 3 broadband stations: UGM, YOGI, and WOJI station, as part of Indonesia-Geophone Network (IA-GE). Inversions were performed using nonlinear Neighborhood Algorithm (NA). We observed Ps phase conversion on the receiver functions corresponding to Moho depth at around 36-39 km. We also observed strong negative phase arrivals at around 10-12 s which might be associated with Indo-Australian subducting slab underneath the stations. The inversion results show the presence of low velocity zone with high Vp/Vs ratio (>1.78) in the middle crust around the study area which could be related to the Merapi-Lawu Anomaly (MLA).

1. Introduction

The study area is located in the southern part of Central Java, where the Indo-Australian plate is subducted beneath the Eurasian Plate since the Cretaceous at an average speed of 6.7 cm/year [1, 2]. This subduction activity may produce a great potential natural hazard such as volcanic eruptions, earthquakes and tsunamis. The latest strong subduction activity in the southern part of central Java was a shallow earthquake on 2006 Mei 26 (Mw=6.3) and Mt. Merapi eruption in October - November 2010 causing more than 5000 casualties. In general, the main geologic and tectonic settings in the Central Java are derived from subduction process including Java trenches, magmatic-volcanic arcs, accretionary prisms, back-arc and fore-arc basins forming a complicated geological setting. This tectonic setting suggests that the crust in the study area is composed several segments accumulated in the southern part of eurasian margin in the Cretaceous [2]. Furthermore, two major wrench faults, the Maria-Kebumen Faults and the Pamanukan-Cilacap Faults met in southern part of Central Java and slip each other, caused many geologic changes in this area [2, 3]. Thus, investigating crustal
characteristics in Central Java is crucial in order to provide additional information for deformation process in this area.

The previous crustal structure studies in Central Java have been done by several researchers (see e.g. [4-7]). The crustal thickness in Central Java is about 34 km based on receiver functions from teleseismic earthquakes data recorded at Merapi Amphibious Network (MERAMEX), although the Vp/Vs ratio cannot be reliably inferred due to noisy data [4]. The results also show an exceptionally strong low velocity anomaly (−30%) in the back-arc crust northward of the active volcanoes (MLA) [4, 5]. The significant reduction of seismic P and S wave velocities is mainly observed in the upper 15 km of the crust between Merapi and Lawu volcanoes [5, 6]. Ambient noise tomography further supports the existence of the MLA (Merapi-Lawu Anomaly) suggesting that the low velocity anomaly is concentrated in the upper 5 km of the crust [7].

Receiver function analysis is a tool to characterize the structure of the Earth by utilizing the seismic waveforms derived from teleseismic events recorded at a three component seismic station [8]. This technique has been widely practiced by some previous researchers to estimate the crustal thickness, Vp/Vs ratio and S wave velocity profile. In this study, we analyze receiver functions to determine the variations of crustal structure: Moho depth, Vp/Vs ratio, and S-wave velocity models beneath YOGI, UGM and WOJI stations using the neighborhood algorithm inversion. The results of this study are expected to improve our knowledge in local crustal models and tectonic development in the southern part of Central Java.

2. Data and method

Our study is based on analysis of teleseismic waveforms recorded on YOGI, UGM, and WOJI stations as part of IA-Geophone seismic network in southern part of Central Java (figure 1). To compute receiver function, we extracted waveforms of the 3 component broadband sensor (BHZ, BHE, BHN) from teleseismic events with magnitude 6 or higher and distance between 30° and 90° recorded from 2008 to 2015 (figure 1). All waveforms were windowed between 10 s before and 50 s after the P arrival. We manually inspected the seismograms to select the best waveform with high signal to noise (s/n) ratio and clear direct P arrivals. We then removed the instrument response, rotated the horizontal seismograms into radial and transverse components and deconvolved those seismograms to generate the receiver functions using computer program for seismology [9]. To control the high frequency noise in the receiver functions, we applied the gaussian filter. In this study, we selected radial receiver function with low gaussian width factor of 0.5 to attenuate the frequency bandwidth greater than approximately 0.3 Hz. To assess the quality of receiver functions, we only used the receiver functions with fit criterion between the observed radial component and the convolution of observed vertical component around 90% or above for further analysis. Finally, we analyzed the selected receiver functions using non-linear Neighbourhoods Algorithm inversion (NA) technique of Sambridge [10] to obtain the velocity profiles beneath seismic stations. The NA technique is a fully non-linear inversion technique based on a random walk in the voronoi cells to search the optimum model using the misfit of the previous models.

To estimate the crustal structure beneath the seismic stations, we inverted the receiver function using the following steps. First, we stacked all radial receiver functions at each station to increase the signal to noise ratio. Second, we cut the receiver functions from 5 s before and 20 s after the direct P wave arrival for the inversion process. We chose this time window to assure that all crustal and lithospheric phase arrivals are included in the inversion analysis. For the inversion process, we divided the initial crustal structure into six horizontal layers: sediment, basement, upper crust, middle crust, lower crust and upper mantle. Each layer contains 4 parameters describing the thickness of the layer (km), Vp/Vs, the S-wave velocity at the top and bottom of each layers. We set the initial parameter after trial and error with low misfit. Then, we computed the NA inversion using 5000 iterations to get the best S wave velocity models.
3. Results and discussion

Figure 2 displays the receiver functions obtained for YOGI, UGM, and WOJI stations. In general the receiver functions show similar waveforms in all seismic stations. The phase delay of direct P phase is observed on the radial receiver functions for all seismic stations indicating the presence of low velocity structure in the near surface. This pattern is probably generated from the superposition of the direct P wave and Ps conversion waves at the interface of basement and sediment layers [11]. Ps Moho conversion waves and the multiples (PpPs and may be PpSs + PsPs) are identified at around 6-8 s and 14-16 s for all seismic stations, respectively. We also observed the combination of positive and negative phase polarities at around 4-6 s on the receiver functions beneath YOGI, UGM, and WOJI seismic stations, which may correlate with the presence of a crustal low velocity zone, Merapi Lawu Anomaly (MLA), as revealed by several studies in this area [5-7]. Moreover, we also find interesting feature on the receiver functions of all seismic stations, in which there are strong negative phase arrivals at around 10 to 14 s. We suggest that strong negative phase arrivals observed on these receiver functions might be associated with the subducted Indo-Australian plate underneath Java Island [5, 12].

S-velocity models resulted from the NA inversions of the stacked radial receiver functions in the three seismic stations are shown on figure 3. The white and solid red lines with green background color represent the average and best fitting of S wave velocity model, respectively. The grey shaded area indicates all models (5000 models) searched in the inversion. The red line on the left represents the best fitting Vp/Vs ratio. The inversion result for YOGI station displayed on figure 3a reveals S wave velocity around 0.53 km/s near the surface interpreted as the sedimentary layer. The S wave velocities then fluctuate from 3.09-3.30 km/s at depth 14 km to 2.90-3.12 km/s at depth 18.9. The low velocity zone characterized by negative velocity gradient is identified at 20-26 km depth, with a S-wave velocity as low as ~2.2 km/s and high Vp/Vs ratio (around 2). Beneath this layer, the S wave velocity increases to 2.82-3.86 km/s by 37.3 km depth. Then, the crust mantle discontinuity is identified at 37.3 km depth characterized by a positive gradient velocity contrast from 3.86 to 4.80 km/s.
The S wave velocity profile derived from the NA inversion for UGM station is shown on figure 3b. The near surface is covered by very low velocity material with a velocity as low as 0.51 km/s. The velocities fluctuate down to ~16 km depth, then decrease with a minimum velocity of ~2.2 km/s at ~18-25 km depth. The crust mantle boundary is observed at a depth of 36.7 km marked by a strong positive velocity gradient (3.75 to 4.98 km/s).

Figure 2. Radial receiver function in (a) YOGI, (b) UGM and (c) WOJI. The right panel is plot the stack of receiver function.

Figure 3. S wave velocity models underneath (a) YOGI, (b) UGM and (c) WOJI stations. The white and solid red lines represent the average and the best fitting model, respectively. The grey shaded area indicates all models (5000 models) sought in the inversion. The red line on the left represents the best fitting Vp/Vs ratio. Bottom panels show the observed and predicted receiver function marked by solid black and blue lines, respectively.
The inversion results for WOJI station, depicted in the right panel figure 3, indicate low-velocity sediment in the near-surface layer, with velocities less than 2.00 km/s. Below this layer the velocity increases up to 3.6 km/s at ~10 km depth. Velocity below that depth then decreases from 3.6 to ~2.6 km/s. The low velocity zone is also observed beneath this station at depth of 20-25 km. The Moho discontinuity appears to be reached at 38 km with average Vs ~3.5 km/s.

The low velocity zone observed beneath all seismic stations at 18-28 km depth is probably associated with the presence of MLA (Merapi-Lawu anomaly) as suggested by other previous geophysical studies [5-7]. Seismic tomography study conducted around this area suggests that low velocity zone at depth 20-30 km in MLA can be interpreted as the influence of the fracturing rocks in the mid crust due to stress accumulation from the subducted Indo-Asutralian slab [5]. Furthermore, S velocity models obtained for all seismic stations also show consistence strong velocity contrast at interface between lower crust and the upper mantle identified as Moho depth location at depth ranging from 37 to 39 km [4]. These values are comparable to other geophysical studies conducted in this area [5, 6].

4. Conclusions
In this study, we presented the crustal properties and S-wave velocity structures derived from teleseismic receiver functions using the non linear NA inversion. We observed that the Moho depth at the southern part in Central Java is ranging from 36 to 39 km. We obtained that the strong negative phase arrivals on the receiver functions at around 10 to 12 s underneath station might be associated with Indo-Australian subducting slab in this area. Low velocity zone can be identified beneath the station in the middle crust (18-28 km) which may be associated with the presence of Merapi-Lawu Anomaly (MLA) with high Vp/Vs ratio (>1.78).

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