Study of Crustal Structure Beneath Station Banjarnegara Indonesia (BJI) Based on Receiver Function Analysis

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Abstract. We applied receiver functions (RFs) analysis to estimated the crustal structures beneath Station Banjarnegara, Indonesia (BJI). We selected teleseismic earthquakes with epicentral distance 30º-90º and magnitude greater than 6 (M > 6) that recorded from 3 component broadband seismograph at the station. We determined crustal thickness, S-wave velocity profiles and ratio of \( v_p/v_s \) using nonlinear Neighborhood Algorithm (NA). We migrated RFs phase to depth by AK-135 global velocity models to identify the depth of the geological structure. From the Ps conversion phase and inhomogeneity of the arrival time, we detected the near surface has a strong anisotropy. We identified delay P phase near surface that associated with thick sedimentary layer in this area at about 2.5 km. Crustal thicknesses, ‘Moho depth’, beneath the station was estimated at depth 28-32 km. The high RFs amplitude phase that might be associated with the presence of Indo-Australian Slab was identified at a depth 140-160 km according to previous studies.

1. Introduction
Banjarnegara Regency is one of the areas in Central Java which is prone to natural disasters. Several disasters such as landslides, floods and earthquakes occurred in areas where most (> 65 %) of the area is in the mountains with steep topography. Based on data from the National Disaster Management Agency (BNPB), there have been at least 118 landslides, 31 tornadoes, 16 floods and 2 earthquakes in the last 20 years [1]. On April, 18th 2018 an earthquake with a shallow depth of 4 km and a magnitude of 4.4 occurred in the area in the Kalibening sub-district (Latitude 7.21 °S and Longitude 109.65 °E) [2]. Even with a relatively small magnitude, this earthquake caused 2 casualties, hundreds of houses to be severely damaged and displaced thousands of people. The source of this earthquake was identified from previously unmapped local fault activity. Several earthquakes in the past have also occurred in this area, as can be seen in Figure 1 [1, 2].

Earthquake events with an epicenter on land originating from active faults in this area need more attention because they are of relatively small magnitude but cause significant damage. Apart from being caused by a shallow depth (< 4 km), this severe damage in many cases often occurs due to amplification of earthquake waves due to soft sediment in this area. The presence of the Banjarnegara BMKG seismic station in the area is very useful in monitoring local earthquakes in the area. In addition, by utilizing the teleseismic seismic wave recordings recorded in a three component
broadband seismograph, it can be used to determine the structure beneath the station, “the receiver functions (RFs)” . Previous researchers have done many analysis of the receiver function to determine the crustal structure under the seismograph station [3-6]. In Indonesia, analysis of the receiver function has been successfully carried out in several regions to determine the crustal thickness, the ratio of $v_p/v_s$ and S wave velocity profiles beneath seismic station [6-12]. Determination of a local velocity model that is more suitable to its geologic conditions is needed in order to accurately determine an earthquake hypocenter. In addition, it is very important to study the structure of the earth's crust to better understand the geodynamics in the Banjarnegara area as a mitigation measure in the future.

![Seismicity Map in Banjarnegara Region, Central Java](image)

Figure 1. Seismicity Map in Banjarnegara Region, Central Java. Red Star Means Significant Earthquake on April, 18th 2018. The Circle is the Earthquake Epicenter, the Blue Inverted Triangle is the BJI Station, and Red Triangle is Active Volcanoes (Earthquakes Data were Obtained from BMKG & ISC Catalogue in 1965-2020)

2. Data and Method
This study used teleseismic earthquake waveforms recorded at BJI Station at coordinates -7.33º N Latitude and 109.71 ºE Longitude. The data was obtained from the BMKG (Meteorology, Climatology and Geophysics Agency) data archive [2]. Earthquake data was selected from the International Seismological Center (ISC) earthquake catalog with an epicenter distance of 30º - 90º and a magnitude greater than 6 (M > 6) [13]. The distance from the earthquake source to the station was chosen to avoid phase contamination of regional and core phases and to ensure that the earthquake ray has a steep incidence angle beneath the station. The research area, epicenter of the teleseismic earthquake and the BJI station can be shown in Figure 2.

![Research Location](image)

Figure 2. The Research Location is in the Banjarnegara area, Central Java, Indonesia. BJI Stations are Shown with an Inverted Blue Triangle. Teleseismic Data is Indicated by a Red Circle Symbol.

2.1. Receiver Function Method
The RFs is a time series function that describes the response of the Earth's structure under a three component broadband seismograph. The conversion phase is formed when a teleseismic wave (distant
earthquake) passes through a layer boundary with an impedance contrast. When body waves, especially P waves meet a seismic discontinuity, the energy of the wave is divided. Some of the energy will be transmitted directly to the earth's surface (direct P wave), partially reflected (reflected wave), and partially converted into an S wave (Ps-converted wave) (Figure 3). The amplitude of the Ps conversion phase is affected by the magnitude of the impedance contrast at the layer boundary. The arrival time of the wave phase, relative to the P wave velocity, the S wave velocity, the depth of the layer boundary (interface), and the distance of the teleseismic earthquake source to the station. A simple earth layer model diagram illustrating the phase conversion of a P wave when it encounters a layer boundary with velocity contrast can be seen in Figure 3 (left). The result of the conversion phase of Ps and its reflected phase (PpPs and PpSs + PsPs) and the synthetic response of the radial component receiver function can be seen in Figure 2 (right) [14,15,10,12].

![Figure 3](image_url)

**Figure 3.** Receiver Function Diagram. The Ps Conversion Phase and the Multiples (PpPs and PpSs + PsPs) Form of a Simple Earth Layer Model

To isolate the conversion of the P to S (Ps) wave phase, a seismogram rotation process of the ZNE (Vertical, North-South and East-West) into the ZRT (Vertical, Radial, and Transverse) coordinate system. To get a receiver function, we applied Iterative Time Domain Deconvolution technique [16]. This technique performs forward modeling, the iterative convolution process of several $E_{IR}(t)$ wavelet models with vertical component seismograms $Z(t)$ to generate signals on radial ($R(t)$) and transverse components ($T(t)$). The response of the local structure, $E(t)$, is determined from the signal model with the minimum misfit between the convoluted synthetic seismogram signal and the observed signal.

$$R(t) = E_{IR}(t) * Z(t)$$

$$T(t) = E_{IT}(t) * Z(t)$$

Where $R(t)$ and $T(t)$ are the radial and transverse component seismograms in the time domain, $E_{IR}(t)$ and $E_{IT}(t)$ are the radial and transverse component receiver function models obtained iteratively. $Z(t)$ is the vertical component of the seismogram and * is the convolution operator $E(t)$ will be equivalent to $E_{IT}(t)$ if the misfit between $R(t)$ and the convolution between $E_{IR}(t)$ and $Z(t)$ is minimum. In this study, the fit criteria were applied between at least 90 %. To eliminate high frequency noise in the receiver function, we used a low-pass Gaussian filter with filter formula as follows: $G(\omega) = \exp \left( -\frac{\omega^2}{4\omega^2} \right)$ [16]. In this study, we used a Gaussian filter with a width of $\alpha = 1.5$ which filters out high frequencies above approximately 0.75 Hz. To locate the geologic structure more exactly, we migrated the receiver functions to depth using Process RF Matlab Program [17]. The global AK135 reference model [18] was used for the migration.
2.2. Neighbourhood Algorithm
The Neighborhood Algorithm (NA) inversion technique is used to estimate the one-dimensional shear wave velocity and \( v_p/v_s \) profile below the station [19]. Prior to the inversion process, the radial component receiver function is stacked from several to increase the signal to noise ratio (S/N ratio). To simplify the inversion process and to ensure that all incoming wave phases originate from phase conversions in the crust and mantle, 5 s signal sampling before and 20 s after the direct P wave phase is performed [8, 9, 12]. In applying NA inversion, there is a selection of initial parameters that must be considered. These parameters consist of: \( Ns1 \), the number of the initial model, \( Ns2 \), is the number of models produced for each iteration, \( Nr \) is the number of voronoi cells which in the next iteration will produce a new model \( Ns \), and maxit, is the total number of iterations required for produce the optimal final model.

In this study, the crust model applied is the 6-layer model which is considered more stable and realistic than several other models of the earth's layer [20]. The crust model used is composed of 6 layers: sedimentary layer, basement, upper crust, middle crust, lower crust layer, upper mantle. Each layer consists of 4 parameters: layer thickness, S-wave velocity at the upper boundary of the layer, S wave velocity at the lower boundary of the layer, and \( v_p/v_s \) ratio. In total, the inversion calculation of the receiver function involves 24 parameters. In this study, \( Ns1 = 60, Ns2 = 30, \) and \( Nr = 30 \) with the number of iterations of 5000 times.

3. Results and Discussion
Twelve (12) RFs under the BJI station radial component arranged based on slowness in the time domain could be seen in Figure 4. From the Ps wave phase form, the difference in the arrival time of several phases (direct P and Ps), it indicates that the structure under the station has quite complex geological features. We assumed from inhomogeneity of the arrival time, the near surface has a strong anisotropy due to its location near an active volcanic and active faults area. The direct P wave was immediately identified as having a delay in arrival time, which is at 1 s. The existence of this delay time in several previous studies [8, 21, 22] is related to the difference in velocity contrast in the layers near the surface, generally due to the conversion phase of the basement layer and sediment underneath the station. The existence of a very high velocity contrast between the bedrock and the sediments above it, converts P waves into S waves (PbS) in this layer (‘b’ mean basement) [22]. In some cases of RFs, the relatively shallow depth of the bedrock compared to the Moho layer and the large contrast of the basement layer with the low velocity sediment above it causes the amplitude of this PbS phase to be higher than the direct P wave or Ps phase originating from the Moho layer. The application of a low gaussian filter (\( \alpha = 1.5 \)) causes the direct P phase and PbS to appear to combine into one phase, so that the P wave immediately appears to be delayed. When processing with a Gaussian filter with a higher width of \( \alpha > 2 \), it will be clear enough to distinguish 2 phases, the direct P wave at 0 s and PbS at 1 s.

![Figure 4. Radial Component RF on BJI Stations in the Time Domain. The Right Panel of the Figure Shows the Stacking of Several RF of Various Slowness](image-url)
The Ps conversion phase originating from the Moho layer is quite evident at 3-4 s arrival time. From several events of various slowness, it can be seen that the arrival time of the conversion phase originating from the boundaries of the upper mantle layer and crust looks quite consistent. At the arrival time of the wave around 15 s there is a quite interesting Ps phase conversion with high amplitude. This phase likely originates from a large plane of layer discontinuity, such as the contrast of the upper mantle to the Indo-Australian Slab. However, this needs to be proven by migrating the time domain receiver function to the depth domain to see its depth and it needs validation from seismicity data and other studies that would be discussed next.

The results of the NA inversion, the S wave velocity model and the $v_p/v_s$ ratio, are good with low misfit results (0.218) (Figure 5 on the left panel). Observed and predicted receiver function could be seen in Figure 5 on the right panel. Under the BJI station, the S wave velocity profile shows the presence of low velocity sediment on the ground to a depth of less than 2.5 km with an S wave velocity from 1.4 to ~ 2.9 km/s. This was also evidenced by the very high $v_p/v_s$ results near the surface (~ 2.81), indicating a low velocity zone near the surface [8, 9]. The presence of low velocity sediment is likely associated with the study area on the edge of the quaternary volcanoes zone [23].

The S wave velocity then increases to 3.39 km/s to a depth of ~ 21.8 km. In the middle crust at a depth of 17.2 to 21.8 km, an increase in the $v_p/v_s$ ratio was observed to reach ~ 1.82. The increase in the $v_p/v_s$ ratio in the middle crust is generally associated with the low velocity zone as found in the previous study (8, 9, 11). This LVZ may be associated with fracturing rock due to stress from slab subduction or it can also be caused by magma activity in volcanoes in the area around the station where to the east and west of the station there are active volcanoes of Mt. Slamet, Mt. Sindoro and Mt. Sumbing. The depth of the Moho is estimated at ~ 29.8 km as indicated by a positive velocity gradient up to ~ 4.18 km / s. The increase in S wave velocity is due to the difference in velocity contrast between the lower crust layer and the upper mantle. The $v_p/v_s$ ratio in the crust varied between 1.7 and 1.82. This high $v_p/v_s$ ratio is probably related to the location of the station which is located near the quaternery volcanoes zone and active faults. It could be related to the presence of partial melt due to geothermal activity and the presence of fluid filled fracture zones.

![Figure 5. S wave Velocity Profile Under BJI Station. The Best-Fitted S Velocity Model are Shown in Red Lines on a Green Background. All Inversion Models are Represented by Gray Areas. The $v_p/v_s$ Ratio is Represented by the Red Line on the Left. The Fittings of the Observation and Prediction Receiver Function are Depicted by a Firm Black Line and a Blue Line on the Right Panel](image)

The results of the migration of the radial component receiver function using the AK-135 global velocity model in this study could be seen in Figure 6 [18]. This migration is important for a clearer interpretation of the location and depth of geological structures discussed. The near surface layer
shows the PbS phase originating from the P to S conversion phase originating from the basement at a depth of ~ 2km (shown by the yellow line in Figure 6). This PbS phase is also confirmed from the velocity of the S wave model and the high $v_p / v_s$ ratio previously discusses. From several RFs based on back azimuth (baz), it is clear that the RFs originating in quadrants I ($baz = 0^\circ - 90^\circ$) and IV ($270^\circ - 360^\circ$) have the same PbS phase form. This PbS phase is not found in the other quadrants. We estimate that that to the north of the station there is a significant contrast in the velocity of the layers near the surface which could be originating from sediment or mountain arcs north of the station as can be seen in Figure 1.

The low velocity zone (LVZ) can also be identified in several RFs in a portion of the quadrant represented by negative amplitude at ~ 20 km depth. This result corroborates the previous discussion regarding the presence of LVZ in the middle crust which may be related to volcanic magma activity or fracturing of rock. The Ps conversion phase originating from Moho was clearly observed and consistent at various back azimuths at depths ranging from 28-32 km indicated by the solid black line in Figure 6. We found thickening of the crust beneath the station originating from RFs from the I and IV quadrants associated with the volcanic arc to the north of the station. The thickening of the crust is in accordance with the concept of isostasy, where the thickness of the crust corresponds to the topographic height on the surface which was also found by some previous researchers with the same method in volcanic areas [24, 25].

The depth of the slab was estimated at a depth of about 140-160 km below the BJI station indicated by a solid red line in Figure 6. We estimated this Ps conversion phase with a strong amplitude due to the P wave passing through the boundary plane between the subduction slab and the upper mantle beneath the station. This can be seen from the inhomogeneity of the depth of the slab which is a dipping structure with a south to north subduction direction. RFs originating from the North (quadrants I and IV) have a shallower slab depth than RFs originating from the South (quadrants II and III). An explanation of the phase of the RFs through a dipping structure could be seen in previous research [4]. The depth of the slab in this area according to previous studies, from global earthquake relocation study and a subduction zone geometry model [26, 27].

4. Conclusion
We estimated the crustal structure beneath BJI station by calculating 12 teleseismic RFs. We inversed using the NA technique to obtain the crustal thickness, the S-velocity structure, and Poisson's ratio. We migrate RFs in the time domain to the depth domain using the AK-135 global velocity model to
identify the depth of the geological structure. We observed lateral variations in the phase RFs with back azimuth, indicating lateral heterogeneity or dipping layers. We identified direct P phase delay near the surface is related to a thick sedimentary layer in this area of about ~2.5 km. The presence of thick sediment near the surface is also confirmed by the results of NA inversion, where the $v_p/v_s$ ratio is very high (~2.81). The crust mantle transition zone, ‘Moho depth’, beneath the BJI station is estimated at depth from 28 to 32 km. The $v_p/v_s$ ratio in the crust varied between 1.7 and 1.82. This high $v_p/v_s$ ratio is probably related to the location of the station which is located near the active volcanic zone and active faults. It could be related to the presence of partial melt due to geothermal activity and the presence of fluid filled fracture zones. The high RFs amplitude phase that might be associated with the presence of Indo-Australian Slab is identified at a depth 140-160 km according to previous studies.

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