Crustal structure beneath Simeulue Island, Indonesia: Preliminary study from a joint inversion of receiver function and surface wave dispersion

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Abstract. Simeulue Island is located on the subduction zone between Indo-Australian and Eurasian plates. The Island is in the forearc basin west of Sumatra Island. Due to subduction process of Indo-Australian plate beneath Eurasian plate, high seismic activities occur around Simeulue Island. Two devastating megathrust earthquakes of 2004 Mw 9.2 Sumatra-Andaman and 2005 Mw 8.7 Nias earthquakes occurred close to the Island. Information of crustal structure may provide better understanding about tectonic characteristics. In this preliminary study, we investigated crustal structure beneath Simeulue Island from three temporary broadband seismometers. Crustal structure was derived from joint inversion of receiver function and surface wave dispersion. S-wave velocity profiles obtained from joint inversion may suggest that the crustal thickness beneath Simeulue Island is at about 20-25 km. S-wave velocity decrease is observed at depth of about 50-60 km depth. This low velocity decrease may be related to the subducting slab of Indo-Australian plate.

1. Introduction

Sumatra Island is located on the boundary of Eurasian and Indo-Australian plates. Along the western coast of Sumatra, the Indo-Australian plate subducts obliquely beneath the Eurasian plate. The slip causes partitioning into trench-normal thrust along the boundary and strike slip component accommodated by Sumatran fault zone [1, 2]. It has been estimated that the dip of Indo-Australian subducting slabs about 10-15° for depth less than 40 km beneath Simeulue Island and about 13° for depth less than 30 km beneath Mentawai Islands [3, 4]. The collision process between Eurasian and Indo-Australian plates causes high seismicity in this region. In the last two decades, two large megathrust earthquakes occurred close to Simuelue Island, i.e. the 2004 MW 9.2 Sumatra-Andaman and 2005 MW 8.7 Nias earthquakes.

Simeulue Island is an outer forearc island. The structure on the island may represent a collision complex between the Indo-Australian and Eurasian plates. Faults trending NE-SW and NW-SE was found on Simeulue Island, with a major fault (Pagaja Fault) found in the northern part. Simeulue Island is mostly made up from a sedimentary sequence deposited during the Oligocene and Miocene epoch. A
A geological map of Simeulue Island is shown in Figure 1. There are five main strata of sedimentary rock found on the main island, i.e. Lasikin Member of Sigulai Formation Tmnl (conglomerate), Sigulai Formation Tms (bedded marl and quartz sandstone), Sibigo Formation Tmsb (coralline limestone), Layabaung Formation Tml (tuffaceous sandstone), Dihit Formation Tmpd (arenite sandstone intercalated with siltstone and claystone) [5].

Figure 1. Geological map of Simeulue Island with major fault is shown in solid line. Red triangles represent location of broadband seismometers used in this study. Inset map shows seismicity in 1960 - 2000 with location of Simeulue Island shown in black square. Red and blue stars represent 2005 Mw 9.2 Aceh and 2005 Mw 8.7 Nias earthquakes.

Crustal structure plays important factor in hazard mitigation. Information on the crustal structure may give us more understanding about tectonic activity. Crustal structure can be derived using seismic tomography method if station coverage is enough. High density of seismic stations may give high resolution of seismic velocity model in two or three dimensional model. However, we will not be able to extract detailed seismic velocity structure if station coverage is not sufficient. Another method to determine crustal structure is by combining receiver function and surface wave dispersion. The method may give information about seismic velocity model in one dimensional. Many studies using joint inversion of receiver function and surface wave dispersion have been carried out to estimate the crustal structure [e.g. 6-8]. Receiver functions are sensitive to the structure contrast beneath the station and estimated by deconvolving vertical component of teleseismic P-wave from the horizontal components (radial and transverse). Receiver function traces consist of direct P wave and its multiples, such as Ps, PpPs, and PpSs+PsPs [e.g 9, 10]. It is assumed that incident angle of teleseismic P-wave is steep, so that the horizontal components contain phases polarized in S-wave direction. Hence, S-wave velocity structure is usually inverted from the receiver functions. On the other hand, the surface waves
are sensitive to the shear-wave velocity structure of the Earth within range of their penetration. So that, it may possible for us determine average Earth structure between the earthquake location and the seismic station from the surface wave inversion. Important characteristic of surface waves is called dispersion, which is wave with different frequencies will propagate with different velocities. Two types of surface waves are Rayleigh and Love waves that have elliptical vertical and horizontal motions, respectively. Surface waves with longer period will travel at deeper Earth layer, which has a higher seismic velocity, and therefore will travel faster. In this study, we investigated crustal structure beneath Simeulue Island using joint inversion of receiver function and surface wave dispersion.

2. Methodology
We computed receiver functions from teleseismic events recorded at temporary broadband seismometers installed at Simuelue Island (Figure 1). The seismometers were installed from December 2005 to March 2006. The data were recorded at a sampling rate of 50 Hz. Table 1 shows teleseismic events used for the computation of receiver functions at each station. We computed receiver functions using iterative deconvolution method [11]. The method calculates the receiver functions by minimizing the difference between observed horizontal component and synthetic receiver function from the convolution of the observed vertical component. Receiver functions were computed by applying Gaussian filter with a width parameter of 1.5, which corresponds to low pass filter with a corner frequency of 0.75 Hz. Gaussian filter was applied to reduce high frequency noise in the calculated receiver functions. To compute surface wave dispersion, we decimated the recorded waveforms into sampling rate of 0.5 s. Example of recorded seismograms depicting surface wave propagation is shown in Figure 2 from station MAUD. In this preliminary study, we first estimated Rayleigh wave dispersion from vertical components. Table 2 shows earthquake information used to estimate surface wave dispersion. We applied multiple filter technique to analyze group velocities from the recorded seismograms [12]. The period range used in this study was between 4 s to 100 s.

Joint inversion was carried out using a program of join96 from a software package of Computer Programs in Seismology [12]. The program applies least square method to invert receiver functions and surface wave dispersion for a S wave velocity model. We used ak-135 velocity model as a starting model with a transition of lower crust at depth of 20 km to the upper mantle at depth of about 36 km. The thickness and Poisson’s ratio for each layer was unchanged during the inversion.

Figure 2. Example of recorded seismograms at station MAUD for surface wave dispersion analysis.
3. Results and Discussions

Figure 3 shows shear wave velocity models from three stations obtained from joint inversion of receiver functions and surface wave dispersion. At station LUAN, left panel shows initial and final shear wave velocity models. Right panels show observed receiver functions (solid lines) with their predicted receiver functions (dashed lines). Observed surface wave dispersion (solid triangles) and predicted surface wave dispersion (solid line) are also shown. From the inverted shear wave velocity profile at station LUAN, we observed shear velocity larger than 4.0 km/s, which may represent mantle shear velocity, at depth of about 20 km. Shear velocity then decreases at depth of 36 km. Low shear velocity is observed at depth of about 50 - 60 km. At station PUTR, shear velocity larger than 4.0 km/s can be observed at depth of about 12 km, which is shallower compared to that of station LUAN. Shear velocity then decreases down to depth of 24 km, and relatively low shear velocity can be observed at depth of 40 - 50 km. At station MAUD, shear velocity larger than 4.0 km/s can be observed at depth of about 25 km. Shear velocity then decreases down to depth of 36 km and increases again. Another low shear velocity can be observed at depth of 50 - 70 km.

Inversion results from three stations suggest that the crustal thickness beneath Simeulue Island is about 20 - 25 km thick. Previous study from a broadband station located at forearc basin in Sumatra Island showed the crustal thickness is about 20 km using HK-stacking method [13]. Seismic velocity decreases observed in this study might be caused by several reasons [e.g. 14-16]. Bostock in [15] suggested thickness from receiver function can be interpreted as the upper limit of the thickness. Other studies also observed evidence of low velocity region such as Alaska subduction zone, Mariana, Honshu, Chile or Northeastern Japan [e.g. 17, 18]. Those studies suggested that low velocity zone might be coincide with the Wadati-Benioff zone. Several studies may also suggest that low velocity zone can be attributed to the partial melting, pressured fluid, or serpentinization [e.g. 19, 20].
Figure 3. Inverted shear velocity profile (left panel). Initial models are shown in dashed lines and final velocity profiles are shown in solid lines. Right panel at top shows observed (solid lines) and predicted receiver functions (dashed lines). Right panel at bottom shows observed (dotted) and predicted surface wave (solid line) dispersion.

4. Conclusions
We carried out analysis of crustal structure beneath Simeulue Island by joint inversion of receiver functions and surface wave dispersion. We manually selected good quality waveform from the recorded data from three temporary broadband seismometers. Total of three teleseismic events and one regional event were used in this preliminary study. We applied iterative deconvolution and multiple filter technique in computing the receiver functions and surface wave dispersion, respectively. A total of five receiver functions were calculated from the three stations. From the inversion results, we suggest that the crustal thickness is about 20-25 km beneath the Island. We also observe low velocity zone that might be related to the Indo-Australian slab.
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