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Upper Crustal Structures beneath Yogyakarta Imaged by Ambient Seismic Noise Tomography

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Abstract. Delineating the upper crustal structures beneath Yogyakarta is necessary for understanding its tectonic setting. The presence of Mt. Merapi, fault line and the alluvial deposits contributes to the complex geology of Yogyakarta. Recently, ambient seismic noise tomography can be used to image the subsurface structure. The cross correlations of ambient seismic noise of pair stations were applied to extract the Green's function. The total of 27 stations from 134 seismic stations available in MERapi Amphibious EXperiment (MERAMEX) covering Yogyakarta region were selected to conduct cross correlation. More than 500 Rayleigh waves of Green's functions could be extracted by cross-correlating available the station pairs of short-period and broad-band seismometers. The group velocities were obtained by filtering the extracted Green's function between 0.5 and 20 s. 2-D inversion was applied to the retrieved travel times. Features in the derived tomographic images correlate with the surface geology of Yogyakarta. The Merapi active volcanoes and alluvial deposit in Yogyakarta are clearly described by lower group velocities. The high velocity anomaly contrasts which are visible in the images obtained from the period range between 1 and 5 s, correspond to subsurface imprints of fault that could be the Opak Fault.

Keywords: MERAMEX, Yogyakarta, Ambient Noise Tomography

PACS: 91.30.Jk *Tomography in Seismology*

INTRODUCTION

Yogyakarta region is part of Central Java that has a complex geological setting. There is Mt. Merapi as active volcano that well know closed to Yogyakarta. On May 26, 2006 at 22:54 UTC a big earthquake had occurred around the Opak Fault with the magnitude as Mw 6.3. In 2010, the explosive eruption at Merapi volcano occurred with blasting and pyroclastic flow. The eruptive activity reached at the peak on November 3-5, and generating many pyroclastic flow which ran southward nearly 17 km in distance [1].

Despite the multiple ongoing processes in the region, much information is needed to understand the shallow geological structure. Previous studies [2,3] applied seismic tomographic methods by using passive and active sources around Central Java including Yogyakarta. The results of the active seismic investigation [2] derived a velocity model for south of Merapi with much higher resolution compared to passive seismic. This study aims to cover the gap of our information on the shallow structure of Yogyakarta by using seismic ambient noise tomography.

Recently in seismological studies, seismic ambient noise recorded at seismic stations is used to retrieve

the coherent part of the wave propagation by cross-correlating it between station pairs. Ambient seismic noise imaging by using this coherent part is used at several locations at regional scale such as in California [4], New Zealand [5], Australia [6-8] to image tectonic structures in the subsurface and sediment thickness.

DATA

MERAMEX or MERapi AMphibious EXperiment was a joint Indonesia - Germany project, aimed to study the characteristics of a volcanic system as part of an active continental margin [2]. The network consisted of 134 seismic stations, with 106 short period and 14 broadband Guralps seismometers, 8 ocean bottom hydrophones, and 6 ocean bottom seismometers. The three-component short-period seismometers (Mark L43D or Guralp CMG40T) were equipped by the Earth data loggers recording with a sampling frequency of 100Hz. The broadband stations were operated with Guralp seismometers (CMG3T and CMG3ESP) and recorders (SAM) [2,3].

In this study we used the random seismic wave field of 27 selected seismic stations that covering Yogyakarta region and conduct the cross-correlation

between two stations to extract Green's function.

FIGURE 1. Map of the seismic stations that were operated around Yogyakarta-Indonesia. There are 27 seismometers that covering Yogyakarta region (black inverted triangle).

DATA PROCESSING

We did cross-correlation of noise signals recorded by two stations to extract the coherent part. This method has been successfully applied in helioseismology [9]. Coherent information of the Earth structure can be extracted from the ambient seismic noise by cross-correlating the vertical component records and retrieve the Rayleigh wave from pairs stations at several days of seismic noise [4]. The Green's functions can be extracted from cross-correlating multiply scattered waves recorded at two different receivers. Green's functions thus obtained can be used to image the velocity structure of a medium [10]. Recently, Rayleigh waves from the empirical Green's functions found from cross-correlations of ambient seismic noise has been applied successfully in several region, such as mapping of the major geological structures in New Zealand like Taranaki and Centerbury basins [5], tomographic imaging to identify the geological structures in Australia [6, 8], study of the Hudson Bay Basin to identify crustal structures beneath the basin in North America [11].

In this study, we followed [8] for data processing procedure. To extract the Rayleigh wave Green's function from vertical component, first, we prepare daily SAC files for each station. This stage is to facilitate the process of seismic data processing and cross-correlation. In the next step to compute the cross-correlations between two stations, we divide each of the full day record into 3600 seconds for each segment and 900 seconds for each segment overlap. Cross correlation operations are performed in frequency domain between all possible station pairs and all available daily records. We then average out

cross-correlation segments to create a daily estimate. These waveforms are dominated by Rayleigh waves that are traveling between pairs of stations.

Then we used a nonlinear tomographic inversion technique to map 2D variations along the raypath between stations to spatial domain. After measuring the Rayleigh wave travel times between station pairs at discrete periods, we first trace the wavefronts with Fast Marching Method (FMM), FMM is a grid-based numerical scheme for tracking the evolution of monotonically advancing interface by seeking finite-different solutions to the eikonal problem [12] for a starting model with a constant velocity model. This process is repeated iteratively through minimizing the difference between observed and modeled traveltimes iteratively by using subspace inversion [13].

For the inversion part, we use an iteratively solving subspace method [13]. FMM can accurately track first order wavefront propagation in 2D heterogeneous environments [12]. The curved wavefronts around the low velocity anomalies illustrate the complex nature of propagation.

RESULTS AND DISCUSSION

We produced Rayleigh wave group velocity at period between 1 s and 8 s. As seen in Fig. 2, we showed the tomographic image at differet periods are sensitive to typical af upper crustal structure beneath Yogyakarta.

Period of 1 s in surface wave are most sensitive to structure typical in depth between 1-2 km [14]. We did checkerboard test to performed a resolution analysis and estimated margin of recovered tomographic images. Our results clearly indicate the presence of volcano locations, basin, and the alluvial deposits that are characterized by low velocity anomalies. Other features show high velocity anomaly which corresponds to the carbonate rock layer and pliocene clastic formation in the eastern part of Yogyakarta.

At the range of 1 s to 5 s, images show a consistent pattern alternating low and high velocities anomalies. Low velocity anomaly probably related with high temperature beneath Mt. Merapi. Low velocity at the southern part probably associated with modern volcanic and alluvial deposits [17]. According the period of travel-time tomography, we estimate the depth of sediment in this part less than 4 km, it is consistent with the feature of low velocity area at southern part Yogyakarta.

The boundary of high and low velocity around Opak river fault can be associated with the fracturing of the rock in the uppermost crust, but in the lower sections, at 15 km depth, this zone is almost invisible [3]. The contrast of the boundary between the low and high velocity anomaly can be interpreted the faults

indication. [16] reported faults in northern and southern part of central Java and clearly illustrates that there were a fault in the north and in the south of central Java [17] including Opak fault.

FIGURE 2. The map view of the tomographic inversion results of Rayleigh wave group velocities at time periods of 1, 2, 4, 5, 6 and 8 s. The black and white colors indicate high and low values of velocity anomaly, respectively.

CONCLUSIONS

We extracted the Green's functions by cross-correlating available station pairs in Yogyakarta, Indonesia. Retrieved Rayleigh waves contain energy in the period range of 0.5 s and 20 s, and arrival times of these surface waves were picked for the available station pairs. Tomographic images derived from the inversion of the group wave velocity of Rayleigh waves are clearly depict the geological structure in the upper crustal beneath Yogyakarta. The results of velocity models are able to describe very well the low velocity anomaly area corresponding to volcanic regions, alluvial deposits, and sedimentary. The model shows the high velocity anomaly that correlated with the location of carbonate rocks. High velocity and low

velocity contrasts which are visible in images between 1 s and 5 s, correspond to Opak Fault.

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