A Non-Linear Method for Hypocenter Determination around Central and East Java Region: Preliminary Result

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Abstract. Java Island is highly active tectonic zone and also has a complex geological system as a result of Indo-Australian plate that subducted under the Eurasian plate. This complexity produces many large and destructive earthquakes. Moreover, Java is a most densely populated region in Indonesia. The precise earthquake location can define and evaluate the seismic hazard in the area. In this study, we determined hypocenter location around the central and east Java region by using a non-linear method. We manually picked P- and S-wave arrival time recorded by BMKG network for the time period of 2009 to 2017. We used the minimum 1D seismic velocity model of ak135 to locate the events. We used some criteria for the determination of event location including (i) at least recorded by 4 station which has clear onset P and S arrival, and (ii) has magnitude (Mw) > 3. The seismicity in the study area is controlled by subduction and many active faults distributed along the Java Island, also clustered in several areas such as Kendeng thrust, Opak river fault, Kebumen, Banyuwangi, and others. The result of this study indicates the accurately main shallow seismicity zones in central and eastern part of Java region, and also confirm the presence of active inland faults. As further studies, we will conduct 1D velocity modeling and relocate the hypocenters using an updated local 1D velocity model beneath the study area.

1. Introduction
Java island is highly active tectonic zone and also has a complex geological system as a result of Indo-Australian plate that subducted under the Eurasian plate with the movement velocities vary from ~ 5.8 cm/yr in the west Java and ~6.5 cm/yr in the East [1]. This complexity produces many large and destructive earthquakes in the study area, such as the 1994 large subduction thrust earthquake (Ms 7.2) that produced a tsunami in Banyuwangi, it was caused by slip over a subducting seamount [2]; and also the 2006 Yogyakarta earthquake (Mw 6.3) that occurred by an inland Opak River fault, its geometry had been determined by SAR interferometry [3]. Moreover, Java is a most densely populated region in Indonesia which is claimed over 73 million people live in Central and East Java region. Due to its high potential seismic hazard, it is important to determine the precise earthquake location that may define the geometrical structure beneath the study area.
Previous studies had been reported to evaluate the seismicity, structure and subduction dynamics beneath the study area, such as a local tomography inversion [4–6], GPS observation [1], and geological active faults mapping [7]. In this study, we determined the hypocenters around Central and East Java region by using a non-linear method that developed by Lomax [8]. The same method had been implemented to relocate the events and compare with BMKG data catalog in West Java [9].

2. Data and Method
We manually picked P and S-wave arrival time data recorded by BMKG network within the time period of 2009 to 2017. There were 34 broadband seismometers distributed around Central, East Java and Bali (Figure 1). The selected events for the determination of event location were (i) at least recorded by 4 station which has clear onset P and S arrival, and (ii) has a magnitude (M_w) > 3. As the quality control of P and S-wave arrival time picking process, we plotted a wadati diagram to indicate the Vp/Vs ratio of the observed data we had.

In this study, we applied a non-linear method to determine the hypocenters by using an NLLoc program that developed by Lomax [8]. This program implements the probabilistic inversion approach of Tarantola and Valette [10], using an oct-tree importance sampling algorithm to produce an estimate of the posterior density function (PDF) for the spatial hypocenter location [11]. The oct-tree algorithm determines the PDF of hypocenter location in 3D by subdividing the sampled cells, where the largest probability has been obtained, into 8 child-cells. Then, the process repeats until the termination criteria have been reached. We also used the minimum 1D seismic velocity model of ak135 to locate the events [12].

3. Results
After the arrival time repicking process, we successfully determined 1,529 events with 11,192 phases for each P and S-waves. The observed arrival times were plotted onto wadati diagram, to independently check the linear relationship between phases (Figure 2). Based on the wadati diagram,
the slope of the line is 0.75 so the Vp/Vs ratio is 1.75. It shows that the points or the arrival times we observed had been fitted to the linear relationship and the quality of P and S-times were good enough to locate the hypocenters.

**Figure 2.** Wadati diagram showing a linear relationship between picked phases. In this study, Vp/Vs ratio is 1.75. The red line indicates deviations from a constant Vp/Vs ratio and/or reading data errors.

The NLLoc results a better performance in determining the hypocenter location than the BMKG catalog (Figure 3). The events applied by non-linear method were distributed more clustered in several areas due to prior manual arrival times picking process (while BMKG preferably uses the automatic picking), the station distribution, the velocity model and different inversion approach used in this study. It is also statistically proved by the histograms of arrival residual times (Figure 4). The NLLoc result has more events which residual time is close to zero, while the BMKG still has some events which residual time is about 0-2.0 sec. The same method in the previous study applied in West Java [9] also shows the sort of significant improvement rather than BMKG data catalog.

**Figure 3.** Comparison of seismicity around Central and East Java region between BMKG data catalog (left) and NLLoc result (right). The colors represent earthquake depth and the blocks are the area used to plot the cross sections shown in Figure 5.
Figure 4. Histograms of RMS residual times of BMKG data catalog (left) and NLLoc result (right).

Figure 5. Cross sections of Central and East Java region: (A) through the Opak River Fault, (B) through Kendeng Thrust in the northern block, (C) earthquake cluster in the south of Java, (D) through Banyuwangi earthquake cluster. The colors represent earthquake depth and the blue line indicates the slab 1.0 model [13].

Based on the NLLoc result, the seismicity in Central and East Java is dominantly distributed in the south of Java. The cross section cross-section B, C, and D (Figure 5) show a compatibility with the lineament of slab model 1.0 [13]. It confirms that those seismicity zones were controlled by tectonic activity. In the block D, there is an interesting clustered in the south of Banyuwangi, where the 1994 large subduction thrust earthquake (Ms 7.2) that produced a tsunami occurred in this zone. The seismicity in the area may relate to the subducting plate behind the seamount [2].

In addition, the shallow clustered events probable controlled by the active inland faults, such as in the block A and in the northern block B which are related to Opak River Fault and Kendeng Thrust activity, respectively (Figure 3Figure 5). The shallow seismicity zone in the Opak River Fault
produced a historical destructive earthquake of the 2006 Yogyakarta (Mw 6.5). As can be seen in the cross-section A (Figure 5), the events may represent the fault plane which more likely east-dipping. The geometry of the Opak Fault observed by SAR interferometry [3] is also considered as east-dipping left-lateral fault that may confirm the hypocenter distribution in the eastern part of the fault.

4. Conclusions

We determined the hypocenter location of 1,529 events around Central and East Java region by applying a non-linear method. Compare with the initial BMKG data catalog, the NLLoc result have a significant improvement to locate the events. The events applied by non-linear method were distributed more clustered in several areas due to prior manual arrival times picking process (while BMKG preferably uses the automatic picking), the station distribution, the velocity model and different inversion approach used in this study. Some of the clustered areas may be controlled by tectonic activity and active inland faults. This preliminary result will be used to conduct 1D velocity modeling, relocate the events, and 3D seismic tomography beneath Central and East Java region for further studies.

Acknowledgments

We are grateful to the Agency for Meteorology, Climatology, and Geophysics (BMKG) Indonesia, as the provider of waveform and catalog data. We thank Prof. Anthony Lomax for NLLoc and Seisgram2K70, the programs he developed, as the tools we used in this study. All figures in this study were made by using The Generic Mapping Tools developed by Paul Wessel and Walter H.F. Smith. This study was also supported by PMDSU 2017 scholarship from the Ministry of Research, Technology, and Higher Education of the Republic of Indonesia.

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