3D Seismic Tomography to Image the Subsurface Structure of “IY” Geothermal Field Using Double-Difference Method and Waveform Cross-Correlation: Preliminary Results

Indriani Yunitasari¹, Andri Dian Nugraha², Mohammad Rachmat Sule³

¹Geophysical Engineering, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganeca 10, Bandung 40132, Jawa Barat, Indonesia
²Global Geophysics Research Group, Faculty of Mining and Petroleum Engineering, Institut Teknologi Bandung, Jl. Ganeca 10, Bandung 40132, Jawa Barat, Indonesia
³Exploration and Engineering Seismology Research Group, Institut Teknologi Bandung, Jl. Ganeca 10, Bandung 40132, Jawa Barat, Indonesia

Email: indrianiyunitasari98@gmail.com

Abstract. “IY” Geothermal Field is located in southern part of Bandung, West Java, Indonesia. This geothermal field is dominated by liquid and vapour conditions. In this study, we used microearthquake (MEQ) waveform and catalog data around the geothermal field to determine 3D seismic velocity through tomography inversion. The data was recorded by 15 stations around “IY” geothermal field area. During ten months of recording, there were 926 MEQ events have been identified. We conducted 3D subsurface seismic velocity by using double difference tomographic (tomoDD) in order to delineate structure around the reservoir. To improve the distribution of initial hypocenter from catalog data, we relocated the MEQ hypocenters using double difference method and waveform cross-correlation to enhance P- and S-wave arrival times as input for tomographic inversion. We updated catalog data and applying threshold of coefficient value that we used is around 0.72-0.82, depends on updated waveforms from cross-correlation method. From 15 stations, there are two stations used threshold value above 0.8 for P-wave and two stations for S-wave, whereas other stations used value of 0.72-0.8. The ongoing process, is to determine seismic velocity structure by applying tomographic inversion. We also know the clustering events near well in geothermal field. The result shows the relocated MEQ hypocenters with 3D velocity model to delineate of geothermal reservoir zone, such as brine and steam, depends on the value of Vp, Vs, and Vp/Vs ratio structures.

Keywords: microearthquake, double difference, waveform cross-correlation

1. Introduction

Indonesia, especially in western Java area, has a high enough potential of geothermal energy. “IY” geothermal field is located in southern part of Bandung, 35 km away from Bandung. This field is surrounded by several mountains, such as Mt. Wayang, Mt. Windu, and Mt. Malabar.

Several previous seismic tomography studies (Vp, Vs, Vp/Vs ratio and attenuation models) using different time period of data around this geothermal field have been conducted[1, 2, 3, 4]. They showed
seismic velocity, attenuation and mapping of MEQ events are important to delineate fracture, permeability, steam and fluid saturated zone.

This geothermal field is dominated by liquid and vapour conditions\cite{5}. To identify those conditions, we used tomography inversion from microearthquake waveforms and the updated catalog data around geothermal fields. We used master event cross correlation to update P-wave and S-wave arrival time, so that we can get more accurate picked phases data\cite{6,7}. Double difference tomography method \cite{8} were used to determine 3D seismic velocities along with hypocenter relocation.

2. Data and Method
In this study, we used microearthquake (MEQ) events from catalog data of “IY” geothermal field in the periods of January 2014 to October 2014. The data were recorded by 15 stations around “IY” geothermal field area. During ten months of recording, there were 926 identified MEQ events. The location of initial hypocenters are obtained by using Geiger Adaptive Damping (GAD) method\cite{9}.

For the accuracy of hypocenter location, the smaller azimuthal gap will give more accuracy at regional / global network\cite{10}. We used the selected data based on azimuthal gap less than 180° and recorded by at least four stations. We then determined the initial 1D Vp and Vs models using VELEST\cite{6,7} method as input for tomographic inversion.

In this study, we updated P-wave and S-wave arrival time from catalog data by applying master event of waveform cross-correlation methods\cite{6,7}. This method use cross correlation function between two waveforms, which is the target waveform and the other waveform as master event. Later on, we conducted double-difference tomography\cite{8} to determine 3D Vp, Vs, and Vp/Vs ratio structures with hypocenter adjustment.

3. Data Processing
3.1. Master Event Cross Correlation
Master event waveform cross correlation\cite{6,7} was used to enhance P- and S-wave arrival times as input for tomographic inversion. The beginning of this process is marked by choosing the master event for each station with the highest signal to noise ratio. If a waveform has high signal to noise ratio, it could be assumed that these waveform has good picking quality and could act as a guidance to improve the previous picking result at the same station. We only applied this method to waveform which has cross correlation value above threshold by seeing the similarity between waveform and master event waveform.

We used specific parameters, such as 0.24 second for the length time of window and shifted every 0.05 second. Threshold in every station has different value, based on the similarity of the waveforms, but overall, we used a threshold value above 0.72.

3.2. Hypocenter Relocation and 3D Seismic Tomography using Tomography Double Difference
Input of this process are absolute catalog data, differential catalog data, 1D velocity model, and the parameter of 3D grid nodes. Absolute data is the catalog data from the previous project report, whereas the differential data is the catalog data obtained from ph2dt, a part of HypoDD software\cite{12,13}. We used ph2dt parameter with maximum distance between event pair and station (MAXDIST) is 28 km, maximum hypocentral separation (MAXSEP) is 2 km, maximum number of neighbors per event (MAXNGH) is 10, minimum number of links required to define a neighbor (MINLNK) is 8. The good link parameter is defined with minimum 8 events\cite{13}.

We used 1D velocity model from previous research by Palgunadi in 2016 using VELEST method\cite{14}. The grid nodes parameter is 2 km x 2 km x 0.5 km for inner station network, and higher grid nodes for further area which far from the target. There are 15 grid nodes for X axis, 19 grid nodes for Y axis, and 14 grid nodes for Z axis.
For the double difference tomography inversion, we weighted the P phase by 1 and S phases by 0.75. There is another weighted for absolute data and differential data, higher weighted on absolute data for the beginning to get the global velocity model, and higher weighted on differential at last for more detail velocity model\(^\text{[13]}\). We set damping parameter based on CND value in the range of 40 – 80\(^\text{[13]}\).

We did resolution test for tomography analysis. There are two resolution test, the first one is checkerboard resolution test, the other one is derivative weight sum (DWS). We used resolution test to determine the inversion result which has good resolution and could be interpreted. Synthetic model velocity has ±20% perturbation on checkerboard resolution test. Output from this model is synthetic travel time that we used as input for inversion with the same parameters. Whereas for the derivative weight sum (DWS) we used value above 100.

4. Result

4.1. Update the catalog data

We selected the threshold value above 0.72 based on master event cross correlation result. The number of updated waveforms in every station are different according to the similarity of the waveform and master event waveform. There are 458 updated P phases and 236 updated S phases. The updated of P- and S-phase using waveform cross correlation method are shown in Figure 1.

4.2. Hypocenter Relocation

The relocated MEQ hypocenters location are more clustered. The distribution of MEQ events especially in the clustered events which could be interpreted as weak zone or may be indicated as a structure with the direction of NNE and has dip to the west.
4.3. **Interpretation of 3D seismic velocity Model**

The vertical cross section (N’-N profile) of 3D Vp, Vs, and Vp/Vs ratio structures are shown in Figure 3. We observed three interesting features namely anomaly 1, zone anomaly 2, and zone anomaly 3, respectively.
Figure 3. Vertical section (N’-N, South-North) of a) Vp, b) Vs, and c) Vp/Vs ratio structures through “IY” geothermal field. Blue and red colors indicate high and low anomaly of Vp and Vs value (in percent deviation relative to initial 1D model). Vp/Vs ratio is plotted on the absolute value. Filed green circle stands for MEQ location. Green dashed line, yellow dashed line, and brown dashed line indicate anomaly 1, 2, and 3, respectively. Reverse blue triangles are station location. Red triangles are volcanoes. And d) the map view of vertical section (N’-N, South-North).
For the interpretation of these anomalies, we referred to previous studies from Gunasekara et al.\cite{15} and Wang et al.\cite{16} which they were interpreted $V_p$, $V_s$, and $V_p/V_s$ structures around geothermal are as shown in Table 1.

### Table 1. Interpretation of anomaly pattern for $V_p$, $V_s$, and $V_p/V_s$ ratio\cite{15,16}

| No | $V_p$  | $V_s$  | $V_p/V_s$ | Interpretation                  |
|----|--------|--------|-----------|---------------------------------|
| 1  | High   | High   | Low       | Pressure Decrease               |
| 2  | Low    | Very Low| High      | Water saturated zone            |
| 3  | High   | High   | High      | Solid Rock                      |

Anomaly 1 has low $V_p/V_s$ with high $V_p$ and $V_s$ at depth -0.5 km to 0.5 km, based on the previous study, this anomaly may be associated as pressure decrease. Pressure decrease occurred probably related to the intensive exploitation that caused transformation from pore pressure that filled with water to pore pressure that filled with steam. Moreover, the transformation from water to steam leads to mineral drying\cite{15}. Our interpretation, anomaly 2 may be related to water saturated zone, with low $V_p$ anomaly, very low $V_s$ anomaly, and high $V_p/V_s$ ratio. This zone is located at depth of about 0.5 km to 1 km at north. Anomaly 3 shows high $V_p$ anomaly, high $V_s$ anomaly, and high $V_p/V_s$ ratio which may be associated with solid rock.

### 5. Concluding Remarks

We have been successfully re-picked for 458 P phases and 236 S phases by applying master event cross correlation. We used threshold value above 0.72 for fairly good correlation. The result of this method produce more accurate picking arrival time data.

We relocated MEQ location by using tomography double difference. The relocated MEQ events show the clustered distribution. This clustered MEQ events may be associated with weak zone and correlates to geological structure of “IY” geothermal field with the direction of NNE structure.

The 3D $V_p$, $V_s$, and $V_p/V_s$ ratio structures through the “IY” geothermal field show some interesting features such as high $V_p$ and high $V_s$ anomalies, and low $V_p/V_s$ ratio value at depth of about -0.5 km to 0.5 km which may related to steam and pressure decrease condition. In the northern part of region, high $V_p/V_s$ ratio coincide with low $V_p$ and $V_s$ anomalies which probably associated with water saturated zone.

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