Reservoir Characterization around Geothermal Field, West Java, Indonesia Derived from 4-D Seismic Tomography

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Abstract. Observation of micro-seismic events induced by intensive geothermal exploitation in a particular geothermal field, located in West Java region, Indonesia was used to detect the fracture and permeability zone. Using local monitoring seismometer network, tomographic inversions were conducted for the three-dimensional Vp, Vs, and Vp/Vs structure of the reservoir for January – December 2007, January – December 2008, and January – December 2009. First, hypocenters location was relocated using joint hypocenter determination (JHD) method in purpose to estimate best location. Then, seismic tomographic inversions were conducted using delay time tomography for dataset of every year respectively. The travel times passing through the three-dimensional velocity model were calculated using ray tracing pseudo-bending method. Norm and gradient damping were added to constrain blocks without ray and to produce smooth solution model. The inversion algorithm was developed in Matlab environment. Our tomographic inversion results from 3-years of observations indicate the presence of low Vp, low Vs, and low Vp/Vs ratio at depths of about 1 – 3 km below sea level. These features were interpreted may be related to steam-saturated rock in the reservoir area of this geothermal field. The locations of the reservoir area were supported by the data of well-trajectory, where the zones of high Vp/Vs were observed around the injection wells and the zones of low Vp/Vs were observed around the production wells. The extensive low Vp/Vs anomaly that occupies the reservoir is getting stronger during the 3-years study period. This is probably attributed to depletion of pore liquid water in the reservoir and replacement with steam. Continuous monitoring of Vp, Vs, and Vp/Vs is an effective tool for geothermal reservoir characterization and depletion monitoring and can potentially provide information in parts of the reservoir which have not been drilled.

1. Introduction
Micro-seismic monitoring in geothermal field provides insight into induced and naturally occurring stress changes. This technique maps active fault failure on shear zones, as well as fluid compression, e.g. [1,2,3]. Intensive geothermal exploitation at the considered geothermal field in West Java, Indonesia, induces micro-seismic events which are monitored by a local seismometer network. The reservoir in this geothermal field is the dominance of the water reservoir [4]. Using micro-seismic data monitored by this network, tomographic inversions were conducted for the three-dimensional Vp, Vs, and Vp/Vs structure of the reservoir. These velocity structures can be used to analyze the presence of water or steam in reservoir, e.g. [5,6,7]. We used micro-seismic data occurred during three years of...
observation from the period of January – December 2007, January – December 2008, and January – December 2009. We used dataset of every year respectively. Only data recorded by at least 3 stations were used. The first dataset which events occurred in 2007, are composed of 453 micro-seismic events and consists of 1842 P wave and S wave phases. The dataset of 2008 are composed of 1439 micro-seismic events and consists of 6663 P wave and S wave phases. Furthermore, the last dataset which events occurred in 2009, are composed of 535 micro-seismic events and consists of 2813 P wave and S wave phases. In purpose to image velocity structure of reservoir with good resolution, we used dimension of 1 x 1 x 0.5 km$^3$ for the parameterization model blocks.

First, micro-seismic hypocenters were relocated using joint hypocenter determination (JHD) method in purpose to estimate best location of sources. We used the best and updated 1-D velocity model from previous study [8] (figure 1). Then using these results, seismic tomographic inversions were conducted using delay time tomography for dataset of every year respectively. The travel times on the three-dimensional velocity model were calculated using ray tracing pseudo-bending method.

Figure 1. The 1-D velocity model used in JHD and as an initial model in tomographic inversion

The results of the processing conducted are three-dimensional velocity structures of Vp, Vs, and Vp/Vs for 2007, 2008, and 2009. These images of velocity structure may be able to characterize the condition and structure of reservoir. We significant found a strong Vp/Vs anomaly that correlates with the production zone. Theoretically, laboratory experiments and field studies suggest that this low Vp/Vs anomaly represents a zone where the pore fluid is predominately vapor, pressure is low, and the shear modulus is increased as a result of the drying of argillaceous material in the reservoir [9,10,11]. These changes probably resulted from the removal of reservoir fluids by production. The four-dimensional or time-lapse tomography can be used to study changes in reservoir structures with time. We detect a significant increment in the strength of low Vp/Vs anomaly. This may be attributed to progressive fluid depletion of the geothermal reservoir.

2. Methodology

2.1. Relocated Hypocenter

The precise 1-D velocity model and hypocenter location are the requirement as an input and initial model for seismic tomography. One of the methods to determine 1-D velocity model is coupled velocity-hypocenter method using Velest program [12]. The velocity models used were obtained using this method [8]. Then, we perform joint hypocenter determination (JHD) to solve the coupled hypocenter model problem for micro-seismic location and relocated 2427 micro-seismic events simultaneously.

2.2. Delay Time Tomography

The pseudo-bending method was used in this seismic tomography study as ray tracing method to determine possible ray path in 3-D velocity model and calculate synthetic travel time from hypocenter
to receiver. Pseudo-bending [13] is an approach in minimization of travel time based on Fermat’s Principle by giving small perturbations gradually on ray paths. This ray tracing algorithm in Matlab environment was developed by Syahputra et al. [14] and Fatkhan et al. [15].

In this study, we applied delay time tomography algorithm [16]. For resolve tomography inversion, least square method [17] was implemented iteratively to minimize the differences between observed and calculated travel times. We also added norm and gradient damping to constrain blocks without ray and to produce smooth solution model, respectively [16]. The inversion algorithm used was developed in Matlab environment.

3. Results and Discussion

Figure 2 shows the distribution of relocated micro-seismic events within study area. The range of hypocenters depth varies between elevations of 0.5 to -7 km. The deep events occurred at elevations of -5 to -6 km (mean sea level = 0 km) and the shallow events occurred at elevations -1 to 0.55 km. The distribution of these micro-seismic events in the east side of study area is well correlated to reservoir area. These events are shallow corresponded to permeability zone in reservoir. Meanwhile in the west side, the distribution of micro-seismic events is deeper than east side. These events correspond to the induced activities caused by injection well. In 2008, micro-seismic activities occurred almost three times greater than other years while these events occurred adjacent to injection well. High micro-seismicity in this area may indicate new fracture zone caused by fluid compression.

![Figure 2](image)

**Figure 2.** The map of the distributions of the relocated micro-earthquake events this study, well trajectory, and monitoring stations.
We then used those distributions of micro-seismic to image velocity structures around geothermal area for every year respectively. The parameterization model blocks used had dimensions of 1 x 1.5 x 0.5 km$^3$, so it can image velocity structure of reservoir with fine resolution. We also applied checkerboard resolution test (CRT) as a forward modeling method to test the reliability of the inversion technique used in tomographic inversion and to see the resolution throughout the model space. We used model anomalies ±10% of the initial 1-D velocity model. The results of CRT models for every year are shown at figure 3. The areas which have a pattern of checkerboard blue – red associate to the good resolution areas. We have the equal numbers of P and S wave phases in tomographic inversion, so the resolution for Vp and Vs are similar. Figure 4 shows the results of delay time tomographic inversion in depth section for Vp, while figure 5 shows the results for Vs. Only areas with good resolution are shown, corresponded to CRT.

![Figure 3. The 3-D structures of CRT model for 2007, 2008, and 2009.](image)

Progressive and significant changes in the Vp and Vs fields occur with time. At elevation -1 km, anomaly of Vp decrease from 2007 to 2008, but increase in strength from 2008 to 2009. The anomaly of Vp at elevation -2 km has different pattern, where this anomaly decrease in strength every year.
from 2007 to 2009. Meanwhile for anomaly of $V_s$, at elevation -1 km, this anomaly increase in strength every year from 2007 to 2009. At elevation -2 km, the pattern is also different where anomaly of $V_s$ decreases from 2007 to 2008, but increase in strength from 2008 to 2009. Factors that affect those changes include lithology, temperature, pore pressure, and pore fluid phase [11].

Figure 5. Tomogram of depth section for $V_s$ anomaly in: 2007, 2008, and 2009 at elevation -1 and -2 km. Only areas with good resolution are shown. Positive anomalies are shown by blue colour and negative anomalies are shown by red colour.

Our interested area are shown in slice E–E’ (or N-S 10 km) and F–F’ (or N-S 11 km). Figure 6 shows the structures of $V_p/V_s$ from 2007 until 2009 in this area. The zones of low $V_p/V_s$ ratio (around 1.6) can be interpreted to be associated with steam-saturated rock, while the zones of high $V_p/V_s$ (around 1.8) can be interpreted to be associated with water-saturated rock [9,10]. In general, the pattern of $V_p/V_s$ anomaly growth is smooth with time. We identified those zones of low $V_p/V_s$ as the reservoir of the considered geothermal field. The reservoir zones are located at 12 - 18 km WE, 8 - 12 km NS, and depth of 1 - 3 km below MSL. The existences of the reservoir area are supported by the data of well-trajectory. The pattern of $V_p/V_s$ anomaly for every year is similar, where the zones of high $V_p/V_s$ are around the injection wells and the zones of low $V_p/V_s$ are around the production wells.

The reservoir in this geothermal field is the dominance of the water reservoir [4]. It becomes interesting when tomographic imaging from 2007 until 2009 identify the zones in reservoir area to be associated with steam-saturated rock. The exploitation and production of the geothermal field can cause changes in the reservoir phase system [11]. The progressive depletion of pore fluid causes the replacement of pore fluid with vapor. In addition, the pressure drop in the reservoir causes a decrease in the boiling point, resulting in boiling and vapor phase is formed.

Figure 7 shows clearly that the volume body of low $V_p/V_s$ anomaly around reservoir area increase in strength fairly over 3-years period. Changes in pore pressure, pore fluid phase, and the water content of minerals caused by steam removal are probably responsible for the changes observed in the anomaly. The decrements of $V_p$, $V_s$, and $V_p/V_s$ anomaly are attributed to steam flooding, while the increments of $V_p$, $V_s$ anomaly and decrement of $V_p/V_s$ anomaly are attributed to pressure change and drying of mineral [11]. Progressive growth in $V_p/V_s$ ultimately results from depletion of liquid water in the reservoir; indeed different effects may be dominant in different parts of the field. The features at
shallow part (elevation ~ -1km) are related to effect of pressure decrease and mineral drying. Meanwhile, the features at deeper part (elevation ~ -2km) are related to replacement of pore water by steam as the predominant effect.

2007 2008 2009

Figure 6. Tomogram of vertical cross-section (North-South) for Vp/Vs ratio anomaly in: 2007, 2008, and 2009 at N-S 10 and 11 km, and well-trajectory (production: black lines, injection: blue lines). Only areas with good resolution are shown. Positive anomalies are shown by blue colour and negative anomalies are shown by red colour.

2007 2008 2009

Figure 7. Volumetric of low Vp/Vs anomaly around reservoir area in 2007, 2008, and 2009.

4. Conclusions
Intensive geothermal exploitation at the considered geothermal field in West Java, Indonesia is causing change in local seismic structure which is detectable using four-dimensional seismic tomography in 3-years of observation. The inversion results indicate the presence of low Vp/Vs at around 1.6 in the reservoir area at elevations of -1 to -3 km, interpreted as steam-saturated rock in the reservoir area of this geothermal field. We detect a significant increment of low Vp/Vs anomaly in the strength and volume body from 2007 until 2009. This progressive growth in Vp/Vs ultimately results from depletion of liquid water in the reservoir.

Continuous monitoring of the three-dimensional Vp, Vs, and Vp/Vs ratio is an effective method of reservoir characterization and depletion monitoring at geothermal field, especially at seismically active
exploited geothermal area. Four-dimensional or time lapse seismic tomography can potentially provide information about depletion or changes of phase in parts of the reservoir that have not been drilled.

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