3D Vp, Vs, And Vp/Vs microseismic tomography imaging on “MA” geothermal field: fluid saturation condition analysis

D S Mahartha¹, A D Nugraha², R M R Sule³

¹ Geophysical Engineering, Faculty Of Mining and Petroleum Engineering, Institut Teknologi Bandung
² Global Geophysics Research Group, Faculty Of Mining and Petroleum Engineering, Institut Teknologi Bandung
³ Exploration and Engineering Seismology Research Group, Faculty Of Mining and Petroleum Engineering, Institut Teknologi Bandung.

E-mail: donny.satrio023@gmail.com

Abstract. “MA” Geothermal Field lies on andesitic volcano highlands in the center of Sunda Arc and has transition system between vapor and liquid-dominated reservoir. The reservoir characteristic has been changed over time caused by fluid injection and production. The objective of the research is to interpret the fluid saturation characteristic inside the reservoir based on 3D Vp, Vs, and Vp/Vs tomography image. Microearthquake (MEQ) activities in geothermal field may relate to changes in stress and fractures’ occurrence. P-and S-wave arrival time from 878 MEQ events are used for tomographic inversion. The initial hypocenters were determined using Geiger Adaptive Damping. To ensure the quality of data, we selected the events according to azimuthal gap and the recorded stations. The P-and S-wave arrival times are updated using waveform cross correlation. VELEST is used to determine 1D seismic velocities as input for SIMULPS12 tomographic inversion with hypocenter adjustment. The results show there are two clusters of MEQ events around “GB” and “WD” mountain. The distribution of MEQ around the fluid injection and production area may be related to weak zones and also reveal a structure with N-NE orientation. According to seismic velocity model, the production area is dominated with vapor (low Vp/Vs ratio value). Vapor dominated area has experienced pressure decrease caused by ongoing exploitation. There is also area that has high fracture density compared to other areas. Area that has high water saturation is situated around GB mountain (high Vp/Vs ratio value).

Keywords : microearthquake, waveform cross correlation, relocation, tomography

1. Introduction

“MA” Geothermal field lies on andesitic volcanic highlands in the centre of Sunda Arc. It is part of a cluster consists of Darajat, Papandayan, Tampomas, and Tangkuban Perahu mountain complex. It has fault with N-NE orientation. The previous microseismic studies around geothermal and volcanic-tectonic system in the southern part of Bandung showed the relationship of seismic and attenuation structure and hot material, steam, fracture/permeability and fluid zones. The reservoir has transition system between liquid and vapor domination. Fluid injection and production operation caused changes in reservoir characteristics. These changes associated with MEQ events. One of the benefit of MEQ monitoring is to delineate the fluid saturation condition through 3D Vp, Vs and Vp/Vs ratio structures.
derived from tomographic inversion. The main objective of this research is to interpret the fluid saturation characteristic inside the reservoir based on the 3D Vp, Vs, and Vp/Vs tomography image.

2. Geological setting

“MA” Geothermal Field lies on volcanic highlands formed by Sunda Arc[^8]. Subduction activity has been going on from Cretaceous Era. Faults with NNE-NE and NW orientation dominate the area. The faults’ pattern holds as the main permeability source on fluid migration. “MA” Geothermal Field is dominated with volcanic units consisted of andesitic rocks. It has five geological formation: Loka, Waringin, Pengalengan, Wayang Windu, and Malabar.

“MA” Geothermal Field has two types of reservoir. Those are deep reservoir and two-phase vapor dominated reservoir. Northern reservoir is dominated with vapor and southern reservoir is dominated with water. Surface manifestations consist of fumaroles and hot springs.

3. Methods

In this study, we used 878 MEQ events as main catalog data composed by 1,890 phases of P wave and 1,890 phases of S wave recorded in 15 stations from January to November, 2016. First we determined the initial hypocenters using Geiger Adaptive Damping[^9]. We used 1-D velocity model from Palgunadi[^10]. Later on, we only selected MEQ events data with azimuthal gap less than 180° and were recorded by at least four stations. This selection reduces data to 308 events.

We improved the arrival time of P and S phase using waveform cross correlation[^11]. Master events recorded on each station will be correlated with other waveforms (Figure 1). Master events have the largest signal to noise ratio compared to other waveforms. We only update P and S arrival time with correlation coefficient higher than 0.75. This value is determined by visual interpretation.

![Figure 1. Example of cross correlation of waveform to enhance arrival times. Left column is data aligned on P arrival determined by catalog data. Right column is data aligned by cross correlation in this study. Numbers in column on the right are the correlation coefficients.](image)

Second, we relocate hypocenters and update 1-D Vp and Vs model using Joint Hypocenter-Velocity Determination inversion on VELEST[^13]. The results show that the MEQ hypocenters form cluster around GB and WD Mountains, while the final 1-D Vp and Vs model increase in every depth. Output from VELEST is used as input for tomoprahic inversion by using SIMULPS12[^14] to determine 3D seismic velocity structures (Vp, Vs and Vp/Vs ratio) with simultaneously improved hypocenters location.
4. Results and discussion

MEQ events distribution form clusters around GB Mountain on the north and WD Mountain on the south. This distribution shows that there are fluid injection and production activities that form weak zones which trigger micro earthquakes. The MEQ events location are distributed around production and injection area appear has N-NE orientation as shown in Figure 2, 3, and 4.

![Figure 2](image1.png)

**Figure 2.** Distribution of epicenter of MEQ events. Filled blue circles stand for MEQ events. Reverse blue triangles for station. Red triangles indicate mountain.

![Figure 3](image2.png)

**Figure 3.** Distribution of MEQ events along South-North (A-B). Filled blue circles stand for MEQ events.
The tomographic inversion results (Figure 5 and Figure 6) show that there are three prominent features including (1) zone with high anomaly of $V_p$ and $V_s$, and low $V_p/V_s$ ratio value which may be associated with vapor dominated area and experienced pressure decrease due to exploitation\cite{15, 16}, (2) zone with low anomaly of $V_p$ and $V_s$, and high $V_p/V_s$ value which may be related to fluid dominated zone around GB mountain\cite{15}, and (3) zone with low anomaly of $V_p$ and $V_s$, low $V_p/V_s$ ratio value which is probably associated with vapor dominated zone close to PB area.

At the cross-section G-G’ (South-North), our interpretation is vapor dominated zone which experienced pressure decrease lies deep and covered with clay cap (zone 1 with grey circle). It is indicated by high $V_p$, high $V_s$, and low $V_p/V_s$\cite{15, 16}. Clay cap is characterized with mineral drying. Pressure decrease may happen because of ongoing fluid production that causes water inside the reservoir pores turn into vapor. The pressure decrease inside the reservoir will increase the rock compressibility and shear modulus. Zone 2 with light blue circle is interpreted as zone with high fracture density compared to other areas.
It is characterized by low $V_p$, low $V_s$, and high $V_p/V_s$ [17][18]. The less significant $V_p$ decrease compared to $V_s$ is because water is less compressive than gas. There is also vapor dominated zone which hasn’t experienced pressure decrease under high fracture density area. This zone may haven’t been exploited since there is no sign of pressure decrease.

![Figure 6](image)

**Figure 6.** Vertical section of G-G’ (South-North) for $V_p$, $V_s$ and $V_p/V_s$ ratio structures. Blue and red color indicates high and low anomaly of $V_p$ and $V_s$. $V_p/V_s$ ratio are plotted on absolute value, blue and red colors stand for high and low value. Reverse blue triangles are station. Red triangles stand for mountain.

5. **Concluding Remarks**

Our tomographic inversion with simultaneously hypocenter relocation results show MEQ events are distributed around the production and injection area and also appears structure with N-NE orientation. We observed low $V_p/V_s$ ratio zone which may be associated with vapor domination. Another prominent feature is high low $V_p/V_s$ ratio area which probably related to fluid dominated around GB Mountain.

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