Utilization of Double-Difference Tomography for Geothermal Exploration: 3D Velocity Structure Interpretation and Fluid Determination

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Abstract. Geothermal surface exploration entails a multi-geoscientific process, which is aimed to define the geometry and characteristics of the geothermal reservoir prior to drilling. Lately, micro-seismic event monitoring is becoming a standard procedure in inferring the structure of the potential geothermal reservoir. However, a good coverage of seismic station and abundant seismic events must be fulfilled in order to map the subsurface structure. Taking advantage of the well-designed seismic station deployed at the “ARD” geothermal field prior to its first drilling, a study of micro-earthquake tomography for 3D reservoir structure is performed in this field. A seismic network of 26 stations was set up for more than eight months from August 2011 within 20 km radius from the centre of the expected reservoir. There were 637 micro-seismic events had been detected and located, which is a very high number of seismicity for a region that is not yet under geothermal development. The purpose of this study is to construct a 3D seismic velocity structure using double-difference tomography and to infer fluid properties, i.e. steam and brine, from the ratio of the P- and S-wave velocity. Double-difference tomography is used to its ability to reduce uncertainties of the model associated with picking and velocity structure. A zone with low P and S velocity anomaly as well as a low ratio of Vp/Vs, which is interpreted as the steam dominated reservoir, is observed. Below this reservoir, there is a high P and S velocity anomaly and a high ratio of Vp/Vs which may be correlate to the non-permeable rock.

1. Introduction

Indonesia is considered as one of the few countries with large geothermal potential. Geophysical exploration plays an important role in geothermal exploration[1]. One of geophysical method is micro-seismicity. A seismic network consists of 26 station was deployed on ARD geothermal field and the result shows that there is a high number of seismicity for a region that is not yet under geothermal development[2]. These micro-seismic events can be useful for tomography inversion as a mean to infer the subsurface structure prior to drilling.

Local tomography has become a relatively routine application for use in geothermal field covered by a dense seismic network. The accuracy of the common tomography algorithms, however, highly depends on several factors, including the network geometry, available phases, and arrival time accuracies. Due
to the presence of noise, the arrival times picked either manually or automatically generally have errors. Recent studies have shown substantial improvements in location precision for earthquakes when waveform cross-correlation (WCC) and event-clustering techniques are used to improve arrival time estimates or determine high-precision relative arrival times[^3].

In this study, we use double-difference tomography to reveal the velocity structures in the ARD geothermal. The WCC and event clustering are also implemented for the first time in the Indonesian geothermal field data to sharpen the subsurface image. Variation of Vp, Vs, and ratio of Vp/Vs is related to lithology and characteristic of reservoir. The velocity structure resulted in this study allow us to determine the reservoir zone as well as the fluid type within the geothermal area.

2. Geological Setting
ARD geothermal field is located in Muara Enim Regency, around 225 km from Palembang, South Sumatra and south-east from active volcano, Mt. Dempo. This area is located close to the intersection of two large geological structures, the Semendo Caldera and the Great Sumatran Fault (GSF) System[^4]. Lithology of this area is lava basaltic, andesite, tuff, and breccia, as a result of Bukit Besar Volcanic Complex[^5]. The background seismicity in the area is influenced by GSF and Sumatra subduction zone underneath[^6,7,8].

There are two structural trends in ARD geothermal field, which are NE-SW and NW-SE trends[^9]. According to the present in-situ stress condition at the study area[^10,11], we interpret that the NE-SW trend is older than NW-SE trend. Thus, NW-SE trend might be more permeable than NE-SW trend.

![Figure 1. Location of ARD geothermal field as indicated by white box][9].

3. Data and Method
A seismic network of 26 station was set up for more than eight months from August 2011 to May 2012. We used a catalogue data which was produced by Institute of Earth Science and Engineering (IESE). 637 local events with magnitude less than 3 were detected and located. We applied double-difference tomography on this field. Double-difference tomography is a joint inversion of earthquake relocation and three-dimensional velocity structure. This inversion, reduces the location error caused by the use of poor velocity models and sharpens velocity imaging near source region[^12].

In this technique, the residual between observed and calculated differential travel time between the two events \(i\) and \(j\) at station \(k\) defined as:

\[
dr_{kij} = (T_{k_i} - T_{k_j})^{obs} - (T_{k_i} - T_{k_j})^{calc}
\]

For further information on the theory and algorithm of the double difference technique please refer to the work of Waldhauser and Ellsworth[^13].
Double-difference uses two types of catalog data which are absolute travel times and differential travel times. We computed differential times using ph2dt program from HypoDD code. Ph2dt program is used to optimize the linkage between the pair events. As a result, there are 18,241 P-phase and 18,341 S-phase pairs. Both absolute and differential travel times were weighting and re-weighting to optimize the result. A checkerboard resolution test is performed to check the quality of the inverted tomogram and to delineate well-resolved area (Figure 2).

![Checkerboard resolution test](image)

**Figure 2.** Checkerboard resolution test. (a) Vp perturbation resolution test and (b) Vs perturbation resolution test.
4. Results and Interpretation

After achieving a great success in checkerboard test, we run the tomography inversion with the real data. The inverted tomogram was then used as a basis of the reservoir characterization. Steam-saturated rocks should appear in the velocity tomogram as a zone with low Vp and low Vs and low Vp/Vs, while water-saturated one have high Vp/Vs\cite{14}. In addition, the poisson ratio will increases from steam-saturated to water-saturated\cite{15}. Studied at Nevado del Ruiz geothermal field and showed that if Vs is lower than Vp and Vp/Vs ration is high, it might indicates the old degassing magma. While low Vp and low Vs indicates alteration or fractures zone\cite{15}.

Figure 3 shows the result of tomoDD inversion in vertical section for NE-SW direction in study area. Green dashed-line is interpreted clay cap\cite{16}. The interpretation of the reservoir fluid property based on the value of Vp, Vs and Vp/Vs made in this study was made according to Ito et al.\cite{14} and Londono and Sudo\cite{15}.

There is a low anomaly in Vp, Vs velocity structure and low ratio of Vp/Vs which is indicates steam. We can also see high anomaly for Vp, Vs velocity structure and high Vp/Vs ratio below steam zone. We interpreted this anomaly as non-permeable rocks. In the Vp/Vs velocity structure, we can clearly see that there is anomaly discontinuity. We interpret this discontinuity as fault system, which is an active fault, because there is fumarole Y on the surface that maybe correlates to this fault.

![Figure 3](image-url)  

**Figure 3.** Schematic diagram derived from vertical section of Vp, Vs and Vp/Vs ratio structure. Blue and red colors indicate high and low anomaly of Vp and Vs structures, respectively. Vp/Vs ratio are plotted on the absolute value.
5. Concluding Remarks
In this study, we showed how the micro-seismic method can be used as a mean to image the subsurface structure and its properties prior to drilling. The success of this study in highlighting the reservoir characteristic was mainly coming from the excellent micro-seismic data used and the careful selection of the input parameters. The results of this study indicate a zone with low Vp and Vs anomaly and also low Vp/Vs ratio which is interpreted may be related to a steam zone. It has thickness of about 1 km and located exactly below the clay cap. Furthermore, we also pick out a velocity discontinuity in Vp/Vs velocity structure which was interpreted as a fault.

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