The Physical Mechanisms of Geothermal Reservoir During Hydraulic Injection Through Microearthquake Tomography

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Abstract. Understanding the physical mechanisms involved during hydraulic stimulation is a key parameter to estimate the fluid flow and permeability increase within the geothermal reservoir. An attempt to infer the mechanical behaviour of the XO geothermal reservoir during injection is performed in this study. Microseismic is a key method for monitoring the percolation of the fluid within reservoir during the injection activity. In this study, we aim to determine the 3D seismic velocity structure of the XO geothermal reservoir using microseismic tomography as well as analyse its mechanical changes due to hydraulic injection using the evolution of the microseismicity. We use the microseismic data from 13 and 16 stations deployed before and after the injection, respectively. A total of 2,827 microseismic events were recorded from 2010 to 2013, in which only 135 microearthquakes were recorded before injection and significantly increased to 2,692 events after hydraulic fracturing. To analyze the mechanical behavior of the reservoir, first the hypocenter location accuracy must improved by using a cross correlation master technique. Then hypocenter relocation as well as the velocity structure is inverted using double difference technique. We use tomographic double difference inversion to determine the structure of Vp, Vs and the ratio Vp/Vs. The results of the 3D velocity model together with the microseismic propagation are used to analyse the changes in mechanical behaviour that occur in the reservoir during and after the hydraulic injection.

Keywords: Geothermal, Microseismic, TomoDD, Master event cross correlation

1. Introduction

Indonesia is one of few countries that has potential in geothermal energy of more than 10 GWe. One of geothermal field in Indonesia is a volcanic type geothermal located in south solok regency, 150 km from Padang city. Later, due to confidential issue, we call this field as XO geothermal field. The dominant structure is aligning in NW – SE direction following the Great Sumatran Fault[1,2] and its seismicity[3,4,5]. In addition, perpendicular structures of NE-SW direction are also observed[6]. This variation of the main structures might be related to the stress rotation in the study area[7].
In this geothermal field, several geophysical data acquisition such as microseismic and magnetotelluric method has been performed. As we know, microseismic is a key method for monitoring the percolation of the fluid within reservoir during the injection activity. The recorded microearthquakes can provide important information about the reservoir. Taking advantage of the abundant microseismic data in this study area, we attempt to infer the mechanical behavior of the XO geothermal reservoir during injection.

2. Data and method
We use the microseismic data from 13 and 16 stations deployed before and after the injection. A total of 2,827 microseismic events were recorded from 2010 to 2013, in which only 135 microearthquakes were recorded before injection and significantly increased to 2,692 events after hydraulic fracturing. The authors use 1D velocity model derived by IESE[6] from microseismic and sonic log data (Table 1).

| Layer | Top Depth [km] | Vp [km/s] | Vs [km/s] | Vp/Vs | Thickness [km] |
|-------|---------------|-----------|-----------|-------|---------------|
| 1     | -2            | 3.45      | 1.92      | 1.8   | 1.7           |
| 2     | -0.3          | 4         | 2.22      | 1.8   | 1.5           |
| 3     | 1.2           | 4.3       | 2.39      | 1.8   | 4.9           |
| 4     | 6.1           | 6.2       | 3.44      | 1.8   | 8             |
| 5     | 14.1          | 8         | 4.44      | 1.8   |               |

To improve the arrival time picking of P and S wave, we used master event cross-correlation method[8,9,10]. The correlation method was done for both P and S wave around the onset of arrival time. This method produce cross correlation coefficient and lag time value. The lag time values of pair events, which has cross correlation coefficient of more than 0.74, are used to update the IESE arrival time catalog of P and S wave. As a result, 694 and 771 of P and S arrival times had been updated.

The updated catalog was then used as an input for tomography method. In this study we use double difference tomography. The principle of this method is, if the hypocenter distance between two earthquakes is smaller than the distance between the earthquake and the station, then the ray path between the two earthquakes against the station is equal[11]. In this technique, the residual between observed and calculated differential travel time between the two events $i$ and $j$ at station $k$ defined as:

$$dr_{kij} = (T_{kij}^{obs} - (T_{kij}^{obs} - (T_{kij}^{cal}))$$

For further information on the theory and algorithm of the double difference technique, please refer to the work of Waldhuser and Ellsworth[11] and Zhang and Turber[12].

3. Result and discussion
The initial locations and the relocated of microearthquakes are plotted in Fig. 1 (a) and (b). It can be seen that the relocated microseismic clusters are more focused compared to the initial location. This improvement is also supported by the fact that the root mean square (RMS) errors of the relocated events are significantly lower. Figure 1c shows the RMS histogram of the catalog data has a RMS range from 0.01 s to 0.1 s with dominant 0.02 s, then histogram RMS relocation result TomoDD shows the smaller RMS range with dominant value 0.01 s. Therefore, we can conclude that the waveform cross correlation and double difference relocation successfully improve the accuracy of the hypocenter locations.
Figure 1. Horizontal and vertical section for (a) microearthquake distribution before relocation (b) after relocation using TomoDD method. (c) Histogram of RMS for comparison before relocation and after relocation.

Figure 2 shows the location of microearthquakes during the injection around the well in the XO geothermal field. The spread of the microearthquakes location show that the injection activity in XO Geothermal field caused propagating weak zones due to increasing pore pressure in the reservoir, which might be inferred from the microearthquake clouds.

It is interesting to note that, at the beginning of the injection-the microseismic events spread to almost every direction. However, after some times (Fig. 2.c) they hit a barrier at the western part of the injection well. This barrier is in agreement with the location of a fault oriented in the NE-SW direction, obtained from the topography map. After this time, the microseismic cloud stagnant at this structure and did not grow up further.

Figure 2. Increased distribution of microearthquake epicenter (a to f) due to drilling on well X from January 13th 2013 (18 microevents) until January 22nd 2013, (1,194 microevents).

A vertical section of the Vp, Vs, and Vp/Vs ratio structures passing through barrier-structure is shown in Fig.3. The boundary structure is marked as the boundary between high velocity and low velocity structure (green dashed line). This structure has NE-SW direction, which is in accordance with structure on the surface obtained by IESE.
4. Concluding Remarks

In this study, we have demonstrated the possibility of injection monitoring using microseismic method. The waveform cross correlation and double difference technique used in this study successfully reduce the uncertainty of the event location by a factor of 2. Furthermore, we showed the evolution of the microseismic events cloud as a function of time during injection at one of the wells in the XO field. A structure oriented at NE-SW direction is found to act as a barrier of the microseismic development. The unique microseismic distribution following the injection activity at XO field, suggest us that faults have different role in facilitating the propagation of the microseismic cloud, which might be correlated with the permeability of the fault core. In the future, a further study on geomechanics is required to address this issue.

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