Steam and Brine Zone Prediction around Geothermal Reservoir Derived from Delay Time Seismic Tomography and Anisotropy Case Study: “PR” Geothermal Field

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Abstract. Development of geothermal production can be conducted in several ways, one of them analyses the fracture or crack and structure within the reservoir. Due to low permeability and porosity value within the reservoir in geothermal field. This crack or fracture provide porosity for fluid storage and permeability for fluid movement and play a major role in production from this kind of reservoir. Structure and polarization direction can be derived from anisotropy parameter and seismic velocity parameter in geothermal field. In this study, we used micro-earthquake data of 1,067 events that were recorded by the average of 15 stations during almost 1-year measurement. We used anisotropy parameter using 3-D shear-wave splitting (SWS) tomography method to represent the distribution of anisotropy medium around the geothermal field. Two parameters produced from the S-wave analysis, which is polarization direction and delay time between fast S-wave and slow S-wave. To determine SWS parameters, we used a rotation of horizontal seismogram including N-S component and E-W component. Furthermore, we used short-time fourier transform (STFT) to calculate lag time and time window based on wave periods. Two horizontal components have been rotated from azimuth 0° to 180° with an increment of 1°. Cross-correlation coefficient used every azimuth of two horizontal components based on delay time with predetermined time window obtained by STFT. When cross-correlation coefficient is high, the corresponding value of delay time and azimuth are chosen as the polarization direction and delay time of SWS. Normalized time different divided by total ray length was used to determine the distribution of crack density. Through correlation of seismic velocity model, crack density, and 3-D anisotropy tomography, we can delineate a geothermal reservoir model. Our results show, high degree of anisotropy and crack density occur in the northern and eastern part of “PR” geothermal field for further development. The result had good correlation with high production of geothermal activities.

Keyword: micro-earthquake, tomography, SWS, geothermal

1. Introduction

The propagation of shear-wave in anisotropic medium leads to the splitting of waveform and arrival time. Anisotropy of the medium, shown by shear-wave splitting (SWS) in local earthquake
seismogram and had been proven toward upper crust [1]. The mechanism divided into two main categories, which are stress induced anisotropy and structural control anisotropy [2]. In the earth crust, the split of shear-wave mainly caused by pressure that parallel with vertical micro-crack [3], the density of crack and the direction of crack can be estimated from the delay time among two separated shear-wave and the polarization given by the fast wave.

Anisotropy is the variation of seismic velocity on its direction [2]. The medium is anisotropic if the value of the physical properties vector is also varied along the direction. In general, there are three major factors responsible for seismic anisotropy: 1) interlayer of lithology; 2) preferred orientation of minerals; and 3) stress-induced fractures and micro-crack that show preferred alignment [3].

The previous study regarding shear-wave splitting using anisotropy parameter (K) has been conducted by Zefeng Li et al [4] similar method had done by Haijiang Zhang et al [5]. This study is the development of a shear-wave splitting tomography method to distribute the spatial distribution of anisotropy in the upper crust using the backpropagation of delay time shear-wave along the ray-path in 1-D and 3-D velocity models at North Anatolian Fault (NAF) northern Turkey.

Through the previous study, shear-wave splitting method using the delay time of SWS may be used in the development of 3-D tomography as a function of anisotropy parameter percentage (K) and determine the crack density in the geothermal field with the assumption of delay time just on the ray-path and horizontal anisotropy is neglected.

In this study, to obtain the value of anisotropy parameter in the positive value, we used non-negative least square (NNSL) method [6]. Furthermore, this method does not including the distance of anisotropy in inversion scheme, so that the ray-path was calculated by pseudo bending principle.

2. Regional Geology
The “PR” Geothermal field is located in the southern area of West Java, approximately 40 km southern of Bandung, Indonesia (figure 1).

Figure 1. The location of “PR” Geothermal Field. Located 40km to the southern part of Bandung City. This field is associate with south mount cluster of west Java Mountain [13]

Also, it is located in the active tectonic area, which is the main structural pattern are on W-NW; NW; and NE direction. These structures are the result of both regional tectonic activities and local volcanic area.

3. Theory
Using the assumption of delay time that accumulated along the ray-path [2] and applying a rotation into two seismograms, then the delay time of SWS can be obtained. Characterization of anisotropy can
be obtained using isotropic slowness \((U)\) through equation of anisotropy coefficient \((K)\) expressed in [5]. It shows a linear relation between the anisotropy percentage \((K)\) and the delay time SWS. Therefore, the nonlinear approximation of iteration is unnecessary. By using this scheme, the calculation does not rely on the initial model.

4. Delay Time Tomography

The data were recorded in January 2015 to 7 December 2015. The microearthquakes were recorded using 15 three-component seismometers that were distributed in the research area. The tomography was calculated using an SIMULPS12 software [3]. The advantage of 3-D velocity model is that the data of P phases and S phases were relatively close. Thus the result of velocity model and hypocentre is improved.

Determining velocity model requires the parameterization of the model. Parameterization is constructed by grid block. The amount and dimension of grid model determined by three parameters: 1) distribution of microearthquakes; 2) depth of microearthquakes; and 3) the zone with high density of ray-path. The grid dimension 1km x 1km x0.5km was chosen from elevation 2km up to 2km at depth (figure 2).

4.1. Checkerboard resolution test

Resolution checkerboard test was experienced on the data to show the area that had a good inversion result and minimum grid space that could be accommodated by the available data. The resolution test used synthetic data to verify the best inversion parameters. Figure 3 shows seismic velocity model perturbation with ±10% of initial 1-D model.

4.2. The Result of Tomography 3-D

Color bar tomography used in this research is red for describing low anomaly of VP, Vs, and ratio of Vp/Vs, whereas blue color indicates high anomaly. Color scale on Vp and Vs is the deviation value through the 1-D initial model. Meanwhile, color scale on Vp/Vs ratio shows the absolute values. Also, the result of seismic velocity inversion, throughout the period of January 2015 to December 7th, has been conducted with 6,776 for both P phases and S phases.
5. Anisotropy

5.1. Determining Window of Shear-wave Splitting
We used short-time fourier transform (STFT) to determine the dominant frequency in the selected time window around picking of S-wave arrival time. The dominant frequency used to calculate the length of waveform’s period. Furthermore, this period is used as pale in cross-correlation between two waveforms.

5.2. Shear-wave Splitting Parameter
Determining SWS parameter, there are the polarizations of S-wave and delay time SWS that were analyzed using cross-correlation between two waveforms with rotated seismogram to radial and tangential coordinate. Figure 4 show an example of seismogram that had been rotated and correlated until it can produce a contour value of cross-correlation between radial and tangential direction. The rotation angle is used from 0° to 180° with the increment of 1°. The coordinate of the highest value of lag time and polarization direction are assumed as SWS parameters.

5.3. Crack Density
The previous study had been done by Vlahovic et al [8], showed crack density had been obtained by normalizing the delay time along the ray-path. Afterward, the normalization on delay time plotted as illustrated in figure 5.

The crack density value is in the range of 4ms/km to 11 ms/km. Dense crack density is located at the eastern part of the study area and vice versa at the opposite side. It is also followed by moderate to high value of crack density. However, the weakness of this method is not able to delineate the anisotropy in the certain depth. Therefore, analyzing the anisotropic area using tomography anisotropy is need to be done.

5.4. Tomography Anisotropy
Since SWS parameters obtained, thus the delay time and polarization direction proceed to acquire the percentage of anisotropy. Percentage of the anisotropy derived in [9].

\[
\Delta t_{\text{SWS}} = |\mathbf{A}| \cos \alpha |\Delta \mathbf{U}|
\] (1)
To obtain $\Delta U$ in the equation (1), is applied a non-negative least square inversion, which is the solution of the minimum deviation error that resulted in the positive value. The parameter of K is the value of percentage constant of anisotropy. The difference of slowness between fast S-wave and slow S-wave velocity is the output that produced by non-negative least square whereas the S-wave velocity model derived from 3-D tomography using the similar data. Figure 6 shows the result of 3-D SWS tomography that illustrated the distribution of anisotropy in “PR” Geothermal field.

![Contour cross-correlation](image1.png)

**Figure 4.** a) Example of cross-correlation result among radial and tangential component. Contour with maximum value indicates by red dot. b) Comparison of hodogram before and after rotation.

![Crack Density](image2.png)

**Figure 5.** Crack density map in the study area. Blue colour indicates denser crack density than red colour.

![Percentage of anisotropy](image3.png)

**Figure 6.** 3-D slice of tomography anisotropy. The blue colour shows high anisotropy while red colour is low anisotropy.

6. Discussion

Output distribution of tomography anisotropy is compared to the perturbation of $V_p$, $V_s$, $V_p/V_s$ ratio, and crack density to delineate the reservoir in the geothermal field (see figure 7). At depth -1.0 km to
0.5 km anisotropy occupied in the production area, however, the higher degree of anisotropy is on the eastern part of production area. High degree of anisotropy lied in the range of 0.3% to 1.5%, supported by the low perturbation of Vp, Vs, and Vp/Vs ratio. The features described as the saturated steam zone in “PR” Geothermal Field. And it is supported by dense crack density in the eastern part and could be interpreted as high permeability area.

Furthermore, at depth -0.5 km to 1 km anisotropy not only lied in production area but also in the injection area. It is caused by intensive fluid injection activities and occupies to the high degree anisotropy in the area. At mean sea level illustrated, on the southern part of the study area, high level of anisotropy associated with Vs lower than Vp and high Vp/Vs ratio is expected as a water zone due to fluid injection activities. Latitude cross section shows toward on the southern part the reservoir becomes deeper, the top of reservoir lied at depth -1 km. The expected water reservoir lied at depth -0.5 km on the northern part and become 0.5 km on the southern part; it is also supported by high degree of anisotropy in the production area that is associated with rapid microearthquakes. On the middle of two mountains, there is occupied a high anisotropy in vertical section that is associated to high Vp/Vs ratio. This anomaly is expected as discharge area with alteration rock, probably the manifestation comes from this features. Generally, percentage of anisotropy was following the regional structure in the study area which is NNW-SSE and NE-SW. The schematic model based on interpretation of Vp, Vs, Vp/Vs ratio, crack density, and tomography anisotropy shown in figure 8.

![Figure 7](image-url)  
Figure 7. The comparison of Vp, Vs, Vp/Vs ratio, and anisotropy in the cross-section C-C” (figure 5). The dashed line bordered the best resolution derived by checkerboard resolution test.
7. Conclusion
Based on Vp, Vs, and ratio Vp/Vs map, the steam zone lies on the northern side of the study area and visible at depth -1 km to 0 km. Steam zone spread out to the eastern part with 3 km wide associated with low Vp/Vs ratio by 1.5-1.68. Water zone lies exactly below the steam zone, however it spreads with high Vp/Vs ratio within 1.78-1.8.

Commonly, dense crack density lies in the eastern part of the study area and vice versa on the opposite side within the range of 4-11 ms/km. Therefore, the area with high permeability can be interpreted as a reference for geothermal development.

The output of SWS parameter depends on the maximum value of cross-correlation. The delay time of SWS has a range of 0.01 to 0.2 second.

High degree of anisotropy and Vp/Vs ratio are possibly caused by interaction among fluid and rock; this interaction leads the occurrence of alteration which is recognized as high anisotropy. Thus, the vertical views indicate the discharge area that supports with manifestation around the location.

References
[1] Crampin S and Y Gao 2006a Physics of the Earth and Planetary Interior 156 1-14
[2] Crampin S 1991 Geophys. J. Int 107 611-623
[3] Crampin S 1994 Geophysics 57(5) 727-735
[4] Li Zefeng, Haijiang Zhang, and Zhigang Peng 2014 Earth and Planetary Science Letter 391 319-326
[5] Zhang H, Liu Y, Thurber C, and Roecker s 2007 Geophysical Research Letter 34
[6] Lawson C L and Hanson R J 1974 Solving least square problems Prentice-Hall Eaglewood Cliffs N.J 340
[7] Evans J R, Eberhart-Phillips D and Thurber H H 1994 User’s manual for SIMULPS12 for imaging Vp and Vp/Vs: A derivative of the “Thurber” tomographic inversion SIMUL3 for local earthquakes and explosions, U.S. Geological Survey Open-File Report 94-431
[8] Vlahovic, Gordana, Maya Elkibi, and Jose A. Rial 2005 Temporal Variation of Fracture Direction and Fracture Densities in the Coso Geothermal Field From Analysis of Shear-Wave Splitting Proceedings Twenty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford California, January 28-30 2002 SGP-TR-171
[9] Ry R V and Nugraha A D 2016 Reservoir Characterization around Geothermal Field, West Java, Indonesia Derived from 4-D Seismic Tomography IOP Conference Series Earth and Environmental Science 29(1):012001
[10] Hasanah M U, Nugraha A D, and Rachmat Sule 2013 Attenuation tomography using
microearthquake (MEQ) data in the “A” geothermal field AIP Conf. Proc. 1554 273

[11] Nugraha A D and Jim Mori 2006 Geophysical Research Letter 33

[12] Nugraha A D, Ahmad Syahputra, Fatkhan, and Rachmat Sule 2013 3-D seismic velocity and attenuation structures in the geothermal field AIP Conf. Proc. 1554 238

[13] https://www.earth.google.com (accessed 8 February 2016)