Analysis of Focal Mechanism for Determine Fault Plane Orientation Using The Moment Tensor Inversion Case Study : West Java Geothermal Field

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Abstract. Micro earthquakes in geothermal field is used to monitor subsurface conditions especially in the reservoir. Micro earthquakes data can be used to determine focal mechanism or fault plane solution with moment tensor inversion method using ISOLA program in MATLAB-GUI. Focal mechanism or fault plane solution describes the orientation of the fault and slip on the fault relative to a geographical coordinate system. The arrival time of the P wave from the 3-component seismometer recording is used in moment tensor inversion and the frequency band that used is 0.02 to 0.08 Hz. The result of inversion with minor error indicated by the value of variance reduction approaching 1 calculated is from modelling waveform synthetic with green function and waveform observation. Fault plane solution in the field that represented by beach ball describes the dominant fault in the North is oblique fault with dip 30–90 degree and in the South is reverse fault with dip 20–85 degree.

1. Introduction
Wayang Windu geothermal field is a research location located about 40 km south of Bandung, West Java. Total generation of 227 MWe with 2 units. The first unit has 110 MWe that has been operating since June 2000 and the second unit with a capacity of 117 MWe began production in March 2009 (Aditya, 2013). Monitoring of micro earthquake activities was conducted to find out the fluid path of injection and confirm the existence of unexpected structures caused production activities. The objective of this study are determine subsurface structure based on fault plane solution with moment tensor inversion method.

1.1. Geothermal system
Wayang Windu geothermal system has a heat source in the form of intrusive rock formation consisting of microdiorite or andesite porphyry dykes with volcanic activities that is <0.23 Ma and there is a conduit connecting the vapor and gas flow from larger intrusive rocks at depth deeper and acting as a source of heat at Wayang Windu Field[1]. A cover layer or caprock in the northern reservoir is a layer of thick lava flows with volcanic deposits comes from the Waringin formation. This layer is rich in clay so it closes fluid path. In the southern part that acts as a shielding layer is a lava flow containing fine-grained sediments and volcanic ash deposits derived from the Waringin Formation. The reservoir of the study area has three parts, namely the first part associated with Puncak Besar and Gambung in the north, two reservoirs in the southern part associated with Mount Wayang and Mount Windu with an area of 22 km². Reservoir boundaries are identified from MT data but can’t provide a clear boundary display so that drilling is used to determine reservoir boundaries[2].

[1] Aditya, 2013
[2]
2. Theory
Focal mechanism or fault plane solution can be describes with coordinate system which is the orientation of the fault and slip on the fault can be parameter to determine the fault geometry such as the style of faulting and stress regimes of a particular region. Earthquake that occurs on the surface can be described as a slip. In practice, earthquake fault can be much more complicated, however most faults can be described in this simple way. Under this assumption, it is possible to describe the motion causing the earthquakes by the orientation of the fault (strike and dip) and slip direction along the fault, slip or rake plane, see Figure 2. Rake is the most common name for the slip direction[3].
2.1. Moment Tensor Inversion

Fault plane solution has been described by double couple which is calculated as the sum of radiation of two single coupling or a pair of coupling. To show the seismic source radiation by combination of nine force pairs, can be shown in Figure 3. Figure 3 describes the illustration of nine force pairs at the coordinate axis where three of them are dipole along the x, y, and z axis and the other six pairs of forces can be grouped into three double couple. From nine component of force pairs only six can be determine because of the conservation of angular and linear momentum[4].

![Figure 3](image)

**Figure 3.** The nine coupling forces of the tensor moment in which x, y, and z represent the north, west and top directions[3]

Mathematically, the moment of tensor can be represented by equation 1.

\[
M = \begin{pmatrix}
M_{xx} & M_{xy} & M_{xz} \\
M_{yx} & M_{yy} & M_{yz} \\
M_{zx} & M_{zy} & M_{zz}
\end{pmatrix}
\]  

(1)

Moment tensor inversion uses a full-waveform method where data is recorded by all components at each seismometer station and inversions are performed to calculate the seismic moment tensor. Based on (Julian et all., 1998), special cases for shear faults and tensile faults. Where in the shear fault, the shift is assumed to occur in the \(x_3\) axis and the discontinuity occurs on the \(x_1\) axis so that \(M_{xz} = M_{zx}\) is a component that is not zero. Whereas tensile faults occur in the \(x_1\) – \(x_2\) field and open towards \(x_3\), there are components that are not zero, namely \(M_{xx} = M_{yy}\) and \(M_{xx} = M_{zz}\). \(M_{xx}\) is located in a cesarean midwife while the \(M_{zz}\) is perpendicular to the fault plane and the moment tensor value is greater than \(M_{xx}\) and \(M_{yy}\)[5].

Following Jost and Hermann in 1989, the displacement \(d\) on the surface at each station of seismogram can be assumed. In case of a point source, the displacement as a linear combination of time-dependent of moment tensor elements like \(M_{kj}\). \(M_{kj}(\xi, t)\) are assumed to have the same time dependence convolved (indicated by the star symbol) with the derivative \(G_{skj}(x, \xi, t)\) of the Green’s functions with regard to the spatial j-coordinate:

\[
u_s(x, t) = M_{kj}(\xi, t) * G_{skj}(x, \xi, t)
\]

(2)

Where:

\(u_s(x, t)\) is component of ground displacement at position x and time t

\(M_{kj}(\xi, t)\) is components of second order, symmetrical seismic moment tensor \(M\)

\(G_{skj}(x, \xi, t)\) is derivative of the Green’s function with regard to source coordinate

\(\xi\) is position vector of point source with coordinates \((\xi_1, \xi_2, \xi_3)\)

\(x\) is position vector of station with coordinates \((x_1, x_2, x_3)\)

The various wave propagation effects through the medium from source to receiver (station of seismogram) can be determine the green function which is represents the impulse response and can be see in Equation 2[6].
The ground motion recorded on seismogram as a convolution of three main factors such as earthquake source effect, Earth crust structure through which the waves propagated and seismometer (Figure 4). Source factor indicated by tensor (m), Green function describes seismogram shape caused by m source, displacement field at station is in the form:

\[
\begin{bmatrix}
    u_1 \\
    u_2 \\
    u_3 \\
    \vdots \\
    u_n
\end{bmatrix} =
\begin{bmatrix}
    G_{11} & G_{12} & G_{13} & G_{14} & G_{15} & G_{16} \\
    G_{21} & G_{22} & G_{23} & G_{24} & G_{25} & G_{26} \\
    G_{31} & G_{32} & G_{33} & G_{34} & G_{35} & G_{36} \\
    \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
    G_{n1} & G_{n2} & G_{n3} & G_{n4} & G_{n5} & G_{n6}
\end{bmatrix}
\begin{bmatrix}
    m_1 \\
    m_2 \\
    m_3 \\
    \vdots \\
    m_n
\end{bmatrix}
\]

Equation 3 can be solved using the least-square method where the G matrix in equation 3 must be transposed to form a square matrix, with the following description:

\[
G^T u = G^T G m
\]

\[
m = (G^T G)^{-1} G^T u
\]

3. Method
Wayang Micro earthquakes data from monitoring reservoir during production recorded with 15 seismogram (GFZ German Research Center for Geosciences – Star Energy). Stages of processing done on the software ISOLA (developed by Dr. E. Sokos, University of Patras, Greece dan Prof. J. Zahradnik, Charles University, Prague[8] where at this stage required completeness of data as input data. Micro seismic events that occur in the geothermal field are recorded by 15 seismometer stations centered on the production and injection area (Figure 5.) then the focal mechanism analysis is carried out at 34 selected events to represent other existing events. According to Havskov and Ottemoller (2010) the data required before inversion tensor moments for analysis of earthquake focus mechanisms include:

1. Full waveform 3-component with the arrival time of P wave and S wave and wave polarization P.
2. Instrument response with correction to eliminate linear trend and recording signals based on the type of seismometer used.
3. The location of the recording station
4. The event location of the hypocenter
5. 1-D Velocity model

Then the processing steps for focal mechanism can be summarized as follows:

1. Generate a green function library, calculate the elementary seismograms, and apply the band-pass filter to the elementary seismograms for each possible event location.
2. Apply the same band-pass filter to recorded waveforms to inversion step.
3. Determine the best solution of moment tensor, event location, and origin time with the least amount of fitting error or variance reduction value.
Analysis of focal mechanism in ISOLA using band-pass filter to minimize noise. Low-pass filtering appropriate to the dataset to remove high-frequency noise and estimating the corner frequency of the source to safely satisfy the point source approximation. Another parameter before the inversion is the seismic source determination by determining the initial depth, the depth interval, and the number of seismic sources. The calculation of green function from the synthetic of each seismogram data resulting the modelling that adjusted to the observation seismogram data to estimate the appropriate parameters at the inversion step. In the inversion step, focal depth is assumed to be constant based on the common of moment-tensor inversion schemes. The quality result in Inversion of moment tensor can be determine from the suitability curve between synthetic and observation seismogram data. The misfit of that curve represented by variance reduction (VR) value with the best fit is to have VR value more than 0.5.

4. Result and Discussion
The result of plotting tensor moment in ISOLA software resulted in an overview of the direction of fault orientation at each event in the hypocentre where the orientation direction of the fault field is depicted by the beach ball in Figure 9. The depiction of the fault direction in the form of strike, dip, and rake on the beach ball facilitate the determination of the type of fault that occurs from the shape of the beach ball, the depth seen from the beach ball color, and the magnitude of the magnitude seen from the size of the beach ball.
Focal mechanism in Wayang Windu geothermal field yield 34 fracture patterns displayed by beach ball (Figure 8) from each hypocenter location where beach ball can determined type fault in subsurface. To determine the type of fracture in production areas in the North and in the South the injection area do ternary diagram plotting the type of fault (Figure 9).

Analysis of the moment tensor solution based on the orientation of the fault plane depicted by the spherical diagrams focused on 34 events (Figure 9) shows that the micro earthquake events observed in the North show the most dominant fractures are strike-slip faults and some other fractures are normal faults. While the micro earthquake event in the South shows the most dominant fracture is strike-slip fault and the other fracture is a thrust fault.
5. Conclusion

The results of mapping the strike and dip values are known that the fracture direction that occurs in the northern field is predominantly Northeast - Southwest (NE - SW) or has a dominant direction N165°E with dip 30° - 90°. The direction and dip of the fracture that occurs has a direction that is in accordance with the structure in the field, namely the structure of the Bandung Basin Boundary which is northeast-southwest (NE-SW) and is a normal fault, so it can be interpreted as the trend same as the structure in the field. The structure contained in the field is a structure that is visible on the surface, while the fracture observed is a fracture that occurs below the surface with a depth of -1.68 to 0.83 m asl so it can be concluded that the surface structure is a normal fault with the Northeast - Southwest (NE - SW) has continuity to the subsurface.

The results of mapping the strike and dip values are known that the fracture direction that occurs in the southern field is predominantly West - East and Northwest - Southeast (NW - SE) or has a dominant direction N90°E with dip 20° - 80° and is a combination of normal and thrust fault called oblique fault, so that it can be interpreted that fractures that occur in the southern part of the field have poor permeability.

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