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Three-Dimensional Inversion of Fluid Flow Electromagnetic Method to Visualize Geothermal Fluid Flow

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ABSTRACT

Fluid flow electromagnetic (FFEM) method is a new geophysical method to monitor dynamic behavior of subsurface fluid flow. The movement of subsurface fluid generates electric field. The phenomenon called “streaming potential” is known as an electrokinetic phenomenon. Both electric and magnetic fields due to subsurface fluid flow are observed at multiple stations in the FFEM method. The distribution of electric and magnetic fields is related to the movement of subsurface fluid. The FFEM method is applicable not only for monitoring geothermal reservoir but also for monitoring oil and groundwater reservoirs.

In order to understand the qualitative characteristics of electric and magnetic fields caused by subsurface fluid flow, a 3-D FDM program that can calculate static electric and magnetic fields for arbitrary resistivity distribution was developed. As a result of some numerical simulations using this program, it was found that a vertical magnetic field is effective for delineating resistivity boundaries like geological faults.

The 3-D inversion program was also developed to determine the location and strength of current sources that are related to the fluid source and sink. Although non-linear least squares method was applied at first, it was not effective because of the high flexibility of unknown parameters. Then Particle Swarm Optimization (PSO), that is one of metaheuristics, was utilized for the 3-D FFEM inversion. As a result of test inversions using simulation data, the 3-D inversion program using PSO was found to be effective for determining both the location and strength of a subsurface current source.

1. INTRODUCTION

A streaming potential associated with fluid flow is known as an electrokinetic phenomenon that occurs at the solid-liquid interface between matrix and water in porous rock. A streaming current is a coupled electric current associated with fluid flow. This current is a local electric current in proportion to the pressure gradient of subsurface fluid. When a streaming current is generated due to subsurface fluid flow, we can observe streaming potentials at the surface. When a static electric current flows through a conducting wire, it is known that the ringed magnetic field of the right screw direction occurs, and it is formulated as Ampere’s law. In the case of a complicated electric current, a magnetic field occurring around a stationary electric current can be calculated using Biot-Savart law. If an electric current, associated with the subsurface fluid flow, is generated, the magnetic field should thereby occur. The estimation of fluid flow direction through streaming current is possible by the subsurface 3-D magnetic field observed at multiple observation points. Figure 1 illustrates the concept of an electromagnetic phenomenon induced by geothermal fluid flow during injection and/or production. There are a few studies focused on such an electromagnetic phenomenon.

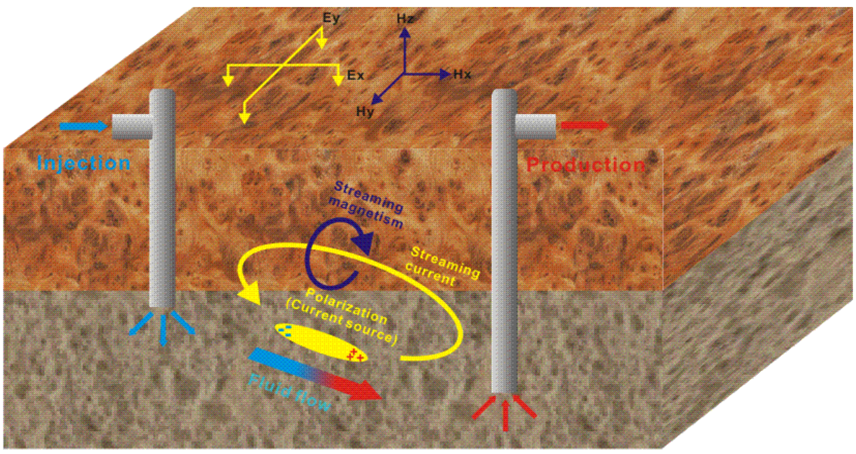

Figure 1: The generation of electromagnetic fields induced by geothermal fluid flow during injection and/or production.

The Fluid Flow Tomography method that we developed is a 4-D geoelectrical method that monitors dynamic behavior of subsurface fluid flow using spatial distribution and transient change of surface streaming potentials, observed simultaneously using multiple potential electrodes at the ground surface (Ushijima et al., 1999). A large quantity of electric wires that extend from each observed electrode to the distant electrode is necessary to carry out observations at the same time using the conventional Fluid Flow Tomography method. Although it is an advantage to be able to perform an observation at the same time as using computer after preparation of survey, it is a disadvantage that a lot of time for measurement preparations is necessary. Therefore, we devised a Fluid Flow Electromagnetic (FFEM) method instead of the Fluid Flow Tomography method to overcome the previous problem

(Mizunaga and Tanaka, 2010). In the FFEM method two electric fields are measured using two perpendicular dipoles and three magnetic fields are observed using small tri-axial magnetometer, simultaneously. Figure 2 illustrates the concept of the Fluid Flow Electromagnetic method.

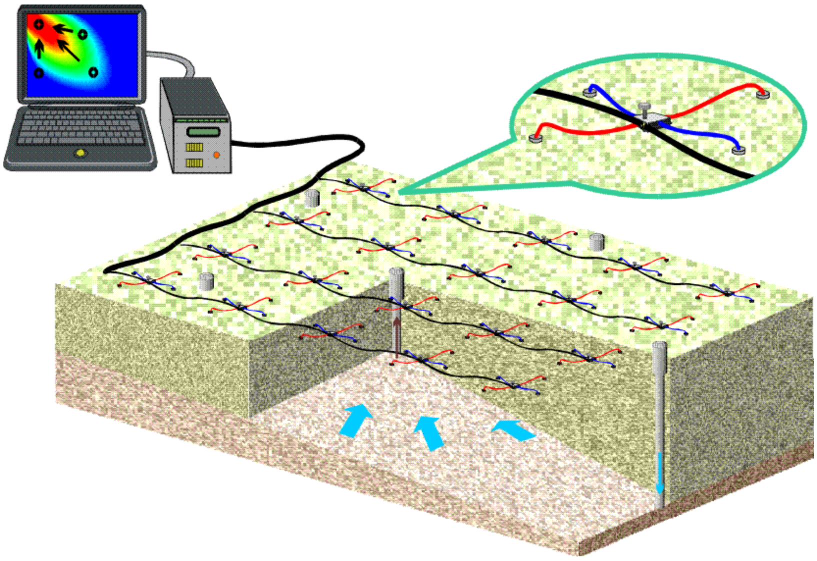

Figure 2: The concept of a measurement system for FFEM method. Three components of magnetic field and two components of electric field are simultaneously observed at multiple stations.

2. 3-D ELECTROMAGNETIC MODELING FOR FFEM METHOD

In order to understand the qualitative characteristics of electric and magnetic fields caused by subsurface fluid flow, a 3-D finite difference program that can calculate both electric and magnetic fields for arbitrary resistivity distribution was developed. This program consists of two calculation stages. At first 3-D potential distribution in case of buried current sources is calculated by using a finite difference method. Then electric field on the surface ground is calculated using surface electric potentials at the first stage. Static magnetic field is calculated using subsurface current flow that is calculated using both electric field and resistivity at subsurface at the second stage. Magnetic field due to a small current source of each discretization block can be calculated using the following Biot-Savart law,

$$d\boldsymbol{H} = \frac{I d\boldsymbol{l} \times \boldsymbol{r}}{4\pi|\boldsymbol{r}|^3}, \tag{1}$$

where $d\boldsymbol{H}$, I, dl, $\boldsymbol{r}$ are magnetic field vector, electric current, unit direction vector of current and direction vector from observed point to current source, respectively. Total magnetic field can be calculated as a summation of magnetic fields due to each discretization block. Figure 3 shows three components of magnetic flux in case of a geological fault model. The left side has a resistivity of 100 Ωm and the right side has a resistivity of 10 Ωm. A point current source (+1A) is located at the center and the buried depth is 2.5 m. As a result of this simulation it was found that each magnetic component is distorted around the resistivity boundary. Using all distributions of the magnetic field, the location of a fault can be estimated. The resistivity boundary (fault) can especially be easily delineated from the vertical component of the magnetic field because vertical magnetic anomalies are distributed along the fault line.

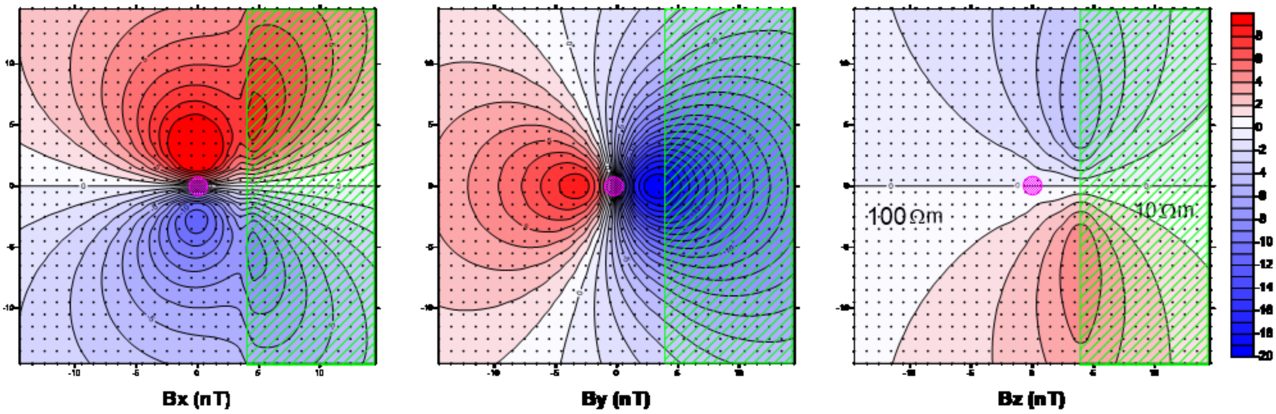

Figure 3: Example of 3-D magnetic modeling in case of a geological fault model. The distribution of three components of the magnetic flux (Bx, By and Bz) are illustrated.

3. 3-D INVERSION OF FFEM METHOD USING PARTICLE SWARM OPTIMIZATION

The 3-D inversion program using magnetic data was developed in order to determine the location and strength of subsurface current flows that are related to the subsurface fluid source and sink, because as a result of numerical simulations the magnetic field was effective in delineating resistivity boundaries. Although non-linear least squares method (Marquardt method) was applied to the 3-D FFEM inversion at first, it was not able to determine the source location and strength with reasonable accuracy because of the high flexibility of unknown parameters. Then Particle Swarm Optimization (PSO), that is one of the metaheuristic methods, was applied to the 3-D FFEM inversion. PSO is based on a simplified social mode, for example bird flocking and fish schooling, and the PSO algorithm contains evolutionary programming similar to genetic algorithms (GA).

Particle Swarm Optimization was developed by Kennedy and Eberhart (1995). PSO is a computational method which simulates social behavior to optimize an object function. A lot of particles that have positions and velocities are utilized in the PSO algorithm. The position in PSO corresponds to an unknown parameter and the velocity corresponds to a parameter correction. The PSO algorithm contains velocity update and position update. The velocity (parameter correction) is updated using the previous velocity and positions of local best particle and global best particle as follows,

$$\boldsymbol{v}_i(t) = \alpha \boldsymbol{v}_i(t-1) + \beta \cdot rand1 \cdot \{\boldsymbol{x}_{LB} - \boldsymbol{x}_i(t-1)\} + \gamma \cdot rand2 \cdot \{\boldsymbol{x}_{GB} - \boldsymbol{x}_i(t-1)\}, \quad (2)$$

where $\boldsymbol{v}_i$, $\boldsymbol{x}_{LB}$, $\boldsymbol{x}_{GB}$ are the *i*-th velocity, local best position of *i*-th particle and global best position of all particles, respectively, and α, β, γ are positive coefficients. The values 0.9, 0.95 and 0.95 are used for α, β and γ, respectively, in this research. The *rand*1 and *rand*2 are random numbers from 0 to 1 and *t* represents a time step or an iteration number. The detailed algorithm of PSO is introduced by Settles (2005). The new position (parameter) is updated using new velocity as follows,

$$\boldsymbol{x}_i(t) = \boldsymbol{x}_i(t-1) + \boldsymbol{v}_i(t) \quad (3)$$

The result of the 3-D FFEM inversion using artificial magnetic data is shown in Table 1. The artificial data for the FFEM inversion was calculated using random numbers and maximum 5% random noises were added to the artificial data. Two current sources are buried at the depth from 0 to 1000m in a horizontal 1000m-square field. Each current source has a 3-D location and a 3-D current value. Twelve unknown parameters were calculated according to the PSO algorithm, using 2400 particles in this case. It was possible to obtain a stable solution for every inversion, except for the traditional inversion using the non-linear least squares method.

Table 1: Example of 3-D FFEM inversion using Particle Swarm Optimization (PSO). Source locations (Qx, Qy, Qz) and current values (Ix, Iy, Iz) of each source are calculated with sufficient accuracy. The upper and the lower numbers of each column are calculated values and true values, respectively.

Source No.	Q*x* (m)	Q*y*(m)	Q*z*(m)	I*x* (A)	I*y*(A)	I*z*(A)
1	221.4 (215.5)	227.3 (239.8)	855.2 (840.9)	-1.91 (-1.68)	-5.29 (-5.19)	-7.85 (-7.39)
2	909.8 (910.6)	470.7 (468.4)	322.6 (323.6)	-8.55 (-8.61)	7.58 (7.53)	5.42 (5.49)

Figure 4 illustrates the magnetic field distributions of artificial observed data and calculated data using the final solution. The solution is found to be correct because the magnetic distributions of observed data and calculated data resemble each other. The remarkable magnetic anomalies appear above the shallower source (Source No.2). The direction of horizontal current flow can be estimated from the vertical magnetic field (Hz) and the existence of vertical current flow can be estimated from the horizontal magnetic fields (Hx and Hy). But magnetic anomalies of another current source (Source No.1) are not clear in all distributions because the buried depth is too deep. As shown in Table 1, the location and strength of two current sources are calculated with sufficient precision using the PSO inversion even though the magnetic anomalies of the deeper source are not clear. As a result of the test inversions using simulation data, the 3-D inversion program using PSO was found to be effective for determining both the location and strength of the subsurface current source.

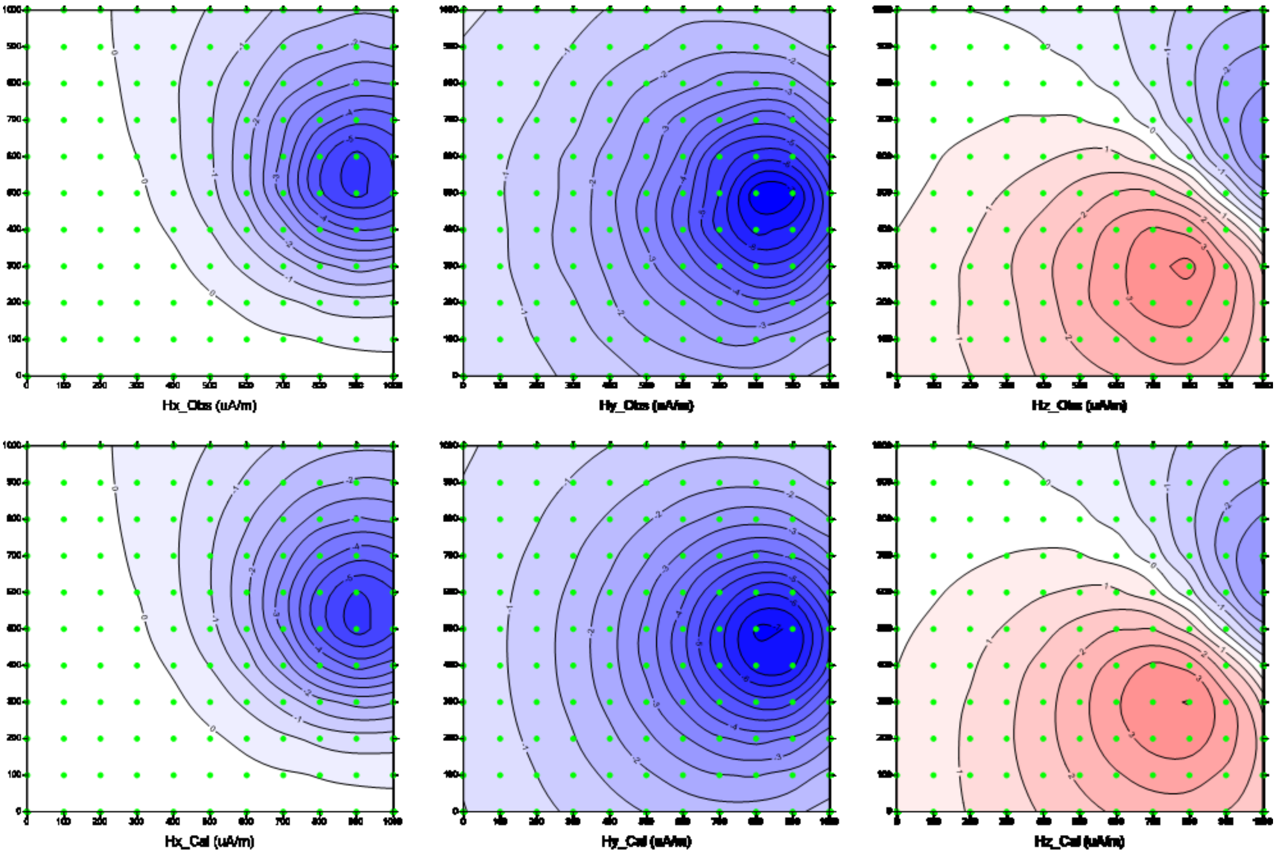

Figure 4: Magnetic field distributions of artificial observed data and calculated result. The simulated magnetic data include maximum 5% random noise.

4. CONCLUSIONS

A 3-D forward program that can calculate static electromagnetic fields for arbitrary resistivity distribution was developed in order to understand the qualitative characteristics of electric and magnetic fields caused by subsurface fluid flow. As a result of some numerical simulations using this program, the direction of horizontal current flow was able to be estimated from the distribution of vertical magnetic field and the existence of vertical current flow was able to be estimated from the horizontal magnetic field. Also, it was found that the vertical magnetic field was effective in delineating resistivity boundaries like geological faults.

The 3-D inversion program was also developed to determine the location and strength of current sources that are related to the subsurface fluid source and sink. Then Particle Swarm Optimization (PSO), that is one of the metaheuristics, was utilized for a 3-D FFEM inversion because a conventional non-linear least squares method was not effective in determining unknown current sources because of the high flexibility of unknown parameters. As a result of test inversions using simulated observed data, the 3-D inversion program using PSO was found to be effective for determining both the location and strength of a subsurface current source.

The Fluid Flow Electromagnetic method is a real time monitoring method used to visualize the dynamic behavior of subsurface fluid flows like geothermal fluid flows. We have developed a new measurement system and a new analysis programs that are key technologies for the FFEM method. The FFEM method is also applicable for petroleum monitoring during EOR and CO_2 monitoring during CCS. The FFEM method will become one of the most important methods to visualize subsurface fluid flows.

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