Three-Dimensional Modeling of TDEM Study for Carbon Capture Storage

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Abstract. TDEM (Time Domain Electromagnetic) method is a sounding geophysical method using electromagnetic wave generated by the electrical current source to image cross section of earth’s subsurface. TDEM using galvanic source (grounded wire) is one of TDEM acquisition technique which has flexible properties for the complex topography of measurement area. Three-dimensional forward and inversion modeling technique of TDEM with galvanic source still develops until now. Three-dimensional modeling is required because three-dimensional structure can influence TDEM signal which has a dimension of z-axis direction only. In this paper, We have been developing a 3D forward modeling program applying finite difference time domain method for 3D subsurface models. We can assess a distribution of TDEM synthetic data affected by 3D model. Using this 3D TDEM modeling program synthetic data has been generated as the function of transmitter and receiver position in 3D model space. Furthermore, this program can be used to simulate a conductivity change of reservoir model as consideration of reservoir monitoring implementation.

Keyword: finite difference, electromagnetic, galvanic, three-dimensional

1. Introduction

TDEM is a sounding geophysical method using electromagnetic wave propagation with galvanic or loop source to image subsurface cross section. For a complex topography field, a galvanic source is required to use because this configuration can be placed anywhere. Three-dimensional forward and inverse modeling of galvanic source is still improved until now. In some discontinuities structure case, we have to model with 3D modeling because TDEM data which generate 1D sounding data but it affected by 3D subsurface model. For example is sand lenses, receiver outside the x and y coordinate of lenses concerning homogeneous structure theoretically. But, a real data measurement, the receiver generates a response from sand lenses. This is an attractive thing to build 3D forward modeling program for TDEM.

Electromagnetic problem formulated by Maxwell equation which integral, finite difference, or analytical solution can solves that. In this paper, we want to solve with finite difference time domain in 3D model space. Because of TDEM sensitive for conductivity distribution, we want to imply 3D forward modeling to detect conductivity change in Carbon Capture Storage (CCS) monitoring project, like Gundih field. Carbon Capture Storage (CCS) pilot project Gundih is project to improve new technique for CO₂ injection monitoring technology which would be better enabled in a shallow reservoir like Ngrayong formation. Resistivity change that is attributed to CO₂ injection may vary from 0.2 to 10 times its initial value [1]. We want to pre-observe CO₂ injection and TDEM data relation, so that, we can understand about TDEM data characteristic and plan acquisition parameter in monitoring CCS project.
case. This research can become preliminary study about 3D TDEM data processing and this is an important thing that best monitoring technique can get the best CCS reservoir which has high CO₂ concentration and low leakage surrounding that reservoir after injection.

2. Basic Concept

2.1 Electromagnetic Concept

Maxwell equation consisted of Gauss law in electricity, Gauss law in magnetism, Faraday law, and Ampere-Maxwell law [2] which formulated by

\[ \nabla \times H = j + \frac{\partial D}{\partial t} = c \] (1)
\[ \nabla \times E = -\frac{\partial B}{\partial t} \] (2)
\[ \nabla \cdot B = 0 \] (3)
\[ \nabla \cdot D = q \] (4)

where \( H \) and \( B \) are magnet field vector (A/m) and magnet induction field vector (T), \( D, q, \) and \( c \) are electric field displacement (C/m²), electric charge (C), and current density (A/m²). Whereas, material characteristic abbreviated to

\[ D = \varepsilon E \] (5)
\[ B = \mu H \] (6)

where \( \varepsilon \) and \( \mu \) are permittivity (F/m) and permeability (N/A²). The geophysical principle for the electromagnetic survey is the transmitter (active or passive) generate induced magnetic field to earth. Induced magnetic field exceeds conductive medium and then galvanize Eddy current inside the medium. Eddy current generate secondary induced magnetic field through to receivers at surface or borehole [3].

2.2 TDEM Measurement Method

Current source type of TDEM survey consisting loop current and dipole current. In this paper, we discuss about dipole source (see Figure 1) because we imply it in CCS which has the deep target and complex topography. Dipole source is more flexible and faster acquisition than loop source. One period of TDEM measurement data called like 50% duty cycle (¼ positive current on, ¼ current off, ¼ negative current on, ¼ current off). The receiver record induced magnetic field when current off. Interest thing caused by transmitter and receiver offset is we obtain TDEM data has two poles in one decay time. This is one of reason, we must generate negative current when TDEM was measuring.

\[ \text{Figure 1. TDEM acquisition with galvanic source [4]} \]

3. Methodology

TDEM dipole source as same as the basic principle of geoelectric when current injection is working. So that, TDEM forward modeling must concern geoelectric forward modeling. In this paper, we apply geoelectric forward modeling equation [5] and electromagnetic [6], it can be written be
where $\varphi$ is an electric potential (V), $\delta$ is Dirac function, $(x_s, y_s, z_s)$ is source coordinate (m). Geoelectric forward modeling generates electric potential distribution, and we determine electric field from a gradient of the potential. Even though, electromagnetic equation use to simulate electroinduced magnetic field decay. Matrix system of geoelectric forward modeling [7] formulated by

$$\mathcal{D}S(\sigma)\mathbf{G}\mathbf{u} = \mathbf{A}(\sigma)\mathbf{u} = \mathbf{q}$$

(9)

D, G, S, u, and q are divergence, operator gradient, conductivity, potential, and current source position. In this paper, delta Dirac function (q matrix) approached by Gaussian function. We have applied conjugate-gradient solver (CG solver) because of large size matrix dimension.

Electromagnetic mechanism formulated to simulate electroinduced magnetic field decay in 3D space model. Electromagnetic wave propagation [8] can be written as

$$B^n = -\nabla \times E^n$$

(10)

$$H^n = \frac{B^n}{\mu}$$

(11)

$$E^{n+1} = \frac{2\gamma - \sigma \Delta t_n}{2\gamma + \sigma \Delta t_n} E^n + \frac{2 \Delta t_n}{2\gamma + \sigma \Delta t_n} \left( \nabla \times H^{n+\frac{1}{2}} \right)$$

(12)

where $\gamma$ and $\sigma$ are permittivity (F/m) and conductivity of medium (S/m). Solving the electromagnetic equation, we use FDTD (finite difference time domain) method [8]. Explicitly, this method can determine unknown parameter from known parameter evaluated before.

4. Result

3D grid model formed by heterogenous grid which expands together with increasing source and transmitter distance. Acquisition design of 3D forward modeling in Figure 2 adjusted to acquisition design of Gundih field which set to an equatorial array and inline array [9]. We do that to consider synthetic data and field data to analysis program quality.

Figure 2. Transmitter and receiver set up of forward modeling
4.1. Homogeneous Synthetic Model
In homogeneous synthetic model case, we have analysed some parameter such us electromagnetic wave propagation and sensitivity at some depths. This matter becomes information to understand signal/synthetic data generated by the program. Because of computation time process equivalent to conductivity medium, therefore we use 100 S/m of conductivity. When t=0 second, induced magnetic field distribution expand and has lower value with increasing of depths. It appropriates to smoking ring principle which TDEM was measuring can forms that. When t=10 second, induced magnetic field distribution spread at a whole of depths because decay mechanism has happened. At sensitivity analysis indicate that increasing depth cause decreasing sensitivity block value. High sensitivity located at source electrode coordinate. So that, when we plan TDEM survey design, we locate the source to target coordinate, although source coordinate can be located outside target with receivers are located to target coordinate, methodically.

![Figure 3. Synthetic data of induced magnetic field z-direction at receiver Rx2, Rx3, Rx8, and Rx9](image)

Synthetic data generated by program at Figure 3 indicate similar pattern with field data. In one decay cycle, signal polarization changes was happened. This polarization changes caused by electromagnetic wave propagation at the surface. So that, to obtain complete TDEM synthetic data, we have to do forward modeling in one period of TDEM measurement.

4.2. Reservoir Block Model
Reservoir model adjusted with field condition of CCS at Gundih, it is sandy lenses structure with clay matrix. Some assumption used to this model are gas conductivity 0.01 S/m, CO₂ gas conductivity 0.2 S/m with 21% fraction, 28-40% of porosity, and geometrical function m=2.15 [10]. To calculate average conductivity of reservoir, we apply Archie law calculation for a heterogenous phase case with a parallel model approach. We get reservoir conductivity is 0.098 S/m (Figure 4).

![Figure 4. Reservoir blocks model](image)
In 3D FDTD simulation at reservoir model, we obtain synthetic data which when \( t=0.2 \) second are signal because the reservoir effect (see Figure 5). That can be analyzed by 3D electromagnetic wave propagation. 3D induced magnetic field indicate that when \( t=0.2 \) second, induced magnetic field propagate at reservoir coordinate and received by receivers at a surface (see Figure 6). Because of the electromagnetic wave velocity is very high, the different time between time of electromagnetic wave propagated in reservoir and received by receivers is very fast. So that, we said that electromagnetic wave was received by receiver represents wave propagation in subsurface model. The generated signal from this program have been compared with signal pattern from analytical formulation. There are gradient change and form curved at detected anomaly time. Stronger signal equivalent with longer distance from transmitter. At long distance, wave propagation can separate signal from different medium when we apply the ray tracing illustration. It is the advantage of 3D modeling which we can analyze synthetic data anomaly from electromagnetic wave propagation. And we know that signal pattern which is generated by subsurface model.

![Bz vs. time graphic](image)

**Figure 5.** Synthetic data of induced magnetic field \( z \)-direction at receiver Rx2, Rx3, Rx8, and Rx9

![Magnetic field distribution](image)

**Figure 6.** 3D Induced magnetic field modeling at \( t=0.2 \) second

TDEM method responsive to conductivity contrast, including to conductivity changes. In CCS case which \( \text{CO}_2 \) injection can affect the conductivity of reservoir. Theoretically, resistivity changes caused by \( \text{CO}_2 \) injection around 0.2 to 10 times from initial value [1]. So that, we consider conductivity of reservoir between 0.1 S/m (initial conductivity) and 0.5 S/m (0.2 times of initial resistivity or 5 times of initial conductivity). The result, conductivity changes can be detected by TDEM method based on FDTD simulation (Figure 7). There are different between blue line and red line, higher conductivity (red line)
has longer decay time because the charge properties. Both lines, can indicate the reservoir signal at t=0.2 seconds like the explanation before about reservoir signal. At the higher conductivity, reservoir impact to signal is stronger than lower conductivity. After t=0.2 seconds, the signal at 0.5 S/m increases gradually but at 0.1 S/m the signal 

\[ B_z \text{ vs time graphic} \]

Figure 7. Synthetic data of induced magnetic field z-direction at receiver Rx5

5. Conclusion
A 3D grounded wire (galvanic source) TDEM forward modeling using FDTD simulate electric field modeling caused by current injection and done in one period TDEM measurement. Synthetic data generated by 3D TDEM forward modeling with FDTD method can indicate anomaly respond which observed from electromagnetic wave propagation in 3D space model. Based on 3D TDEM with FDTD, TDEM method can give conductivity changes respond in reservoir model and also prove that one-dimensional data of TDEM affected by three-dimensional structure.

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