Marine controlled-source electromagnetic sounding on submarine massive sulphides using numerical simulation

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Recently, controlled-source electromagnetic methods are widely used for shallow sub-seafloor explorations. In this paper, we propose a new controlled-source electromagnetic method using an autonomous underwater vehicle (AUV) for the exploration of submarine massive sulphides (SMS). A numerical simulation code for 2.5-D or 3-D electromagnetic field in the frequency domain is employed in order to estimate electromagnetic responses from possible conductivity structures. As a result, we confirmed that we could detect the area of SMS effectively using Ty-Hx and Tz-Ez for transmitter and receiver. This is because the electric field is attenuated and the electric flux is concentrated to the interior of conductive zones. We also confirmed that the effects of topography were relaxed using normalized electromagnetic fields in the simulation. Based on our results, we think that the new controlled-source electromagnetic method is realizable.

1. INTRODUCTION

Recently, controlled-source electromagnetic (CSEM) methods are widely used for shallow subsurface exploration to estimate resistivity structure in detail. This method is also used for surveying oil and natural gas resources in deep sea¹⁾. These days, theoretical and experimental attempts have been initiated to survey submarine massive sulphides (SMS) using electromagnetic methods. Kowalczyk⁴⁾ surveyed SMS using an EM method with a magnetic source, although the sounding depth was limited within several meters.

In conventional marine CSEM methods, we need to connect a survey vehicle and an EM transmitter using a long cable, and also connect the EM transmitter and receiver using a cable. However, in practice, we must tow cables at some height to the seafloor because of rough topography (e.g. chimneys) around SMS. Therefore, it is difficult to investigate shallow sub-seafloor structure. In this research, we propose a new marine CSEM method to solve this problem using autonomous underwater vehicles (AUV), which could be kept closer to the seafloor, moving an EM transmitter. Therefore, so we can carry out the exploration of SMS effectively.

In CSEM method, the behavior of electric and magnetic fields are determined by the arrangement of dipole sources against survey targets. Therefore, it is important to consider the effective arrangement of transmitter and receiver in case of the structure

including low resistivity anomaly. Moreover, we need to include the location of each source electrodes to the numerical modeling because the source-receiver separation will be quite shorter than the conventional CSEM survey.

In this research, we developed a new finite element program for a 2.5-D model space that accommodates the effects of topography around SMS. We also employed a finite difference method program for 3-D developed by C. J. Weiss and S. Constable (2006)⁷⁾. We discussed the feasibility and sensitivity of the new marine CSEM method which uses AUV, considering real deep-sea exploration.

2. METHOD

In this paper, we employed a 2.5-dimensional (2.5-D) simulation to deal a two dimensional (2-D) structure. The 2.5-D simulation is a numerical calculation assuming 3-D EM field from artificial source over 2-D earth. The 2.5-D simulation is a useful method when the behavior of earth structure is similar to 2-D like active fault or across structure. In order to simulate 2-D earth model (x-z plane) and 3-D electric dipole source (x-y-z space), we must apply the Fourier transform to y-component of electric (**E**) and magnetic field (**H**) and source terms. Then, we calculate the Maxwell equation 2-D and wave domain³⁾. Assuming a time-dependence of $e^{i\omega t}$, the electric field **E** and magnetic field **H** are described by Maxwell's equations:

$$\nabla \times \mathbf{E} = -\hat{z}\mathbf{H} - \hat{z}\mathbf{M}_s \quad (1)$$

and

$$\nabla \times \mathbf{H} = \hat{y}\mathbf{E} + \mathbf{J}_s \quad (2)$$

where $\mathbf{M}_s$ and $\mathbf{J}_s$ are the impressed magnetization and electric currents, respectively, and the impedivity $\hat{z} = i\mu\omega$ and the admittivity $\hat{y} = \sigma + i\varepsilon\omega$ are used. Applying the Fourier transform to each component of $\mathbf{E}$ and $\mathbf{H}$ and source terms of equation (1) and (2) with respect to y as

$$\hat{\mathbf{F}}(x, k_y, z, \omega) = \int_{-\infty}^{\infty} \mathbf{F}(x, y, z, \omega) e^{-ik_y y} dy \quad (3)$$

we obtain two coupled governing differential equations for $\hat{E}_y$ and $\hat{H}_y$. After applying Galerkin method, we obtain the linear equation. This global linear matrix is solved using a sparse Left-Looking LU decomposition method developed by Davis (2006)²⁾. The other components are obtained from the space derivatives of $\hat{E}_y$ and $\hat{H}_y$. These space derivatives are calculated using moving least-square (MLS) interpolant method. Moving least square is a method of reconstructing shape functions from a set of point data via the calculation of a weighted least squares measure biased towards the region around the point where the reconstructed value is requested. When we solve this linear equation and employ the inverse Fourier transform, the 3-D electric field in the model is derived, finally.

We also employed a 3-D finite differential simulation to deal with a three dimensional structure. The detail of 3-D simulation is written in C. J. Weiss and S. Constable (2006)⁷⁾. This 3-D simulation can simulate the 3-D electromagnetic field directly, but this method cannot simulate the model including topography.

3. MODEL

Preliminary explorations were conducted to survey SMS around the world. For example, Von Herzen et al. (1996)⁶⁾ reported that the resistivity of SMS as $0.21\Omega\text{m}$, of basalt as $2.35\Omega\text{m}$ and of sea as $0.3\Omega\text{m}$. In this study, we assume the SMS and chimney mound to be a simple rectangular block when we employ the 2.5-D simulation. We also assume the SMS to be a simple disk when we employ the 3-D simulation. We arrange the height of transmitter and receiver to be 20m above the seafloor. The boundary condition is assumed that the electric and magnetic fields are equal to be zero in the far area. We consider that the representative models of submarine massive sulphides like figure 1 for 2.5-D simulation and figure 2 for 3-D simulation. In figure 1 model, we change the thickness of SMS and also changed topography while the depth position of SMS is fixed to be 20m.

Figure 1 Simulating model of 2.5-D simulation.

Figure 2 Simulating model of 3-D simulation.

The meshes used in this study have been generated with “Triangle”, a 2-D mesh generator described by Shewchuk (1996)⁵⁾ which permits a general triangular mesh. We arrange a transmitter having a y-directed current dipole above the anomaly. In this model, we set the topography around SMS assuming the Izena cauldron (METI Agency for Natural Resources and Energy and JOGMEC, 2011)³⁾. In this model, we arranged the transmitter

(a) Results received from the normalized electric field calculating from the model without topography and with topography.

(b) Results received from the normalized horizontal magnetic field calculating from the model without topography and with topography. magnetic fields normalized with respect to those

Figure 3 Separation of the effect of SMS from the effect of topography

above the anomaly, and fixed the source amplitude as 50A and the frequency as 10Hz. We also fixed the dipole length as 4 m which can be possible to carry with AUV in practice. We changed the distance between the source dipole and receiver dipole, and then compared the received electric amplitude. Before these numerical simulations, we calculated the electric amplitude of receiver noise per ampere. In practice, the receiver vibrates while AUV moves in the seawater. We consider it as the random noise due to vibration of the receiver. We assume the predicted noise level of electric and magnetic field as 5×10^{-9} V/m and 2×10^{-6} A/m, respectively. Assuming the vibration noise appear to be white, we stack 64 data set to lower the moving noise to one eighth in the amplitude. We also consider the systematic error due to positioning error. In practice, the position of AUV has the determination error since GPS system cannot be used in the sea water. As an example, we assume the source AUV has the horizontal location error of 1m. In figure 2 model, we change the depth of SMS and the direction of the transmitter and receiver. In this model we set the transmitter far from the anomaly. We also set the dipole moment as 4 Am.

4. RESULTS AND EXAMINATION

We show the numerical results for figure 3 employing 2.5-D simulation and figure 4 employing 3-D simulation. In figure 3 (a), the transmitter is arranged to y-directed and the receiver is arranged to y-directed. In figure 3 (b), the transmitter is arranged to y-directed and the receiver is arranged to x-directed. The horizontal axis means the offset from source to receiver (SMS exist from 20m to 120m for offset). The vertical axis means the thickness of SMS. The contour color depicts the attenuated amplitude of the calculated electric and

calculated for anomaly-free model. The contour line depicts the attenuated amplitude divided by noise amplitude. The non-hatched area shows the detectable area of SMS. As shown in figure 3, the received normalized amplitude goes up when the thickness of low-resistivity anomaly becomes larger. We also could see that the normalized electric and magnetic amplitude becomes similar even though these models have the difference in topography. Therefore normalized amplitude is useful when there is topography in the model.

In figure 4, we changed the depth of SMS in case of Tz-Ez and Ty-Hx for transmitter and receiver. We set the transmitter in the origin of the coordinate axes. In this case, the horizontal axis means the x-coordinates and vertical axis means the y-coordinates. The dashed line shows the area of

Figure 4 Seabed distribution of normalized amplitude for Tz-Ez and Ty-Hx.

SMS. The contour color depicts the normalized electric and magnetic field. When the depth becomes shallow, the attenuating rate of electric and magnetic field amplitudes also become larger. From figure 4, we could see that SMS is not imaged entirely using Tz-Ez. However the normalized field of Tz-Ez is larger than all the rest case. We could also see that the shape of SMS is imaged entirely using Ty-Hx. This is because when we used the transmitter of Tz, the electric flux is concentrated to conductive zone and is penetrating to upward vertically in the xy-plane. This hypothesis is confirmed to see the various depth changed cases. When the depth position of SMS becomes shallow, you can see that the normalized electric field shows the shape of anomaly exactly. This is because when the depth position of SMS becomes shallow, the electric flux goes up to xy-plane near from the area of anomaly.

In case of Ty-Hx, we consider that the conductive anomaly under the transmitter would form a short circuit of electric current around SMS so that the observed magnetic field becomes lower. From the case of Ty-Hx, we can see that the received magnetic normalize field shows the area of SMS entirely regardless of the depth position. We consider that the magnetic field is calculated from the integration of electric field, so the magnetic normalize field shows the area of SMS entirely.

5. CONCLUSIONS

In this study, we compared the behavior of electric and magnetic fields as a function of the position and altitude of source and receiver using a CSEM scheme we propose for the exploration of shallow structure around SMS. The results of the simulation indicate the possibility of our CSEM method to be applied for the exploration of SMS. We also find that it is possible to lower the effects of topography around the SMS when the normalized amplitude is used. We also find that the Tz-Ez gives us the largest normalized amplitude and the Ty-Hx gives us the entirely image of SMS. Through all numerical calculations, we would like to conclude that our CSEM method is realizable for SMS exploration. Our next plan is to analyze real data that are acquired around SMS near from Bayonnaise knoll and Iheya Calderon.

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