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Three-dimensional electromagnetic modeling of sea and topographic effects on electromagnetic field induction by grounded electrical source airborne transient electromagnetics (GREATEM) survey systems

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SUMMARY

A grounded electrical source airborne transient electromagnetics (GREATEM) survey was performed at Kujukuri beach in central Japan, where an alluvial plain is dominated by sedimentary rocks and shallow water. A reliable resistivity structure was obtained at a depth range of 300–350 m both on land and offshore, in areas where low-resistivity structures are dominant (Ito et al., 2011). Another GREATEM survey was performed at northwestern Awaji Island, where granitic rocks crop out onshore. Underground resistivity structures at depths of 1 km onshore and 500 m offshore were revealed by this survey. The absolute resistivity found onshore was much lower than existing results. To circumvent this problem and understand the reason for the inaccurate results, we used a three-dimensional (3D) electromagnetic (EM) modeling scheme based on the staggered-grid finite-difference (FD) method (Fomenko and Mogi, 2002) to study the effects of oceanic saltwater (or the sea effect) on EM field induction when conducting GREATEM surveys at coastal areas with topographic features. The models consisted of two adjacent layers with different conductivities; the sea was given as a thin sheet of a good conductor placed on top of a uniform half-space earth medium. The EM responses were calculated for different positions of grounded electrical sources (10, 20, and 300 m) landward from the coastline. The uniform half-space earth medium resistivity varied from a resistive host rock (100 ohm-m) to a highly conductive host rock (1 ohm-m).

The effects of the sea on EM field induction by the GREATEM survey system depended on the position of the ground electrical source relative to the coastline. For example, the sea effect was much larger when the source position was located 10–20 m from the coastline (e.g., the Awaji Island survey) than when the source position was 300 m from coastline (e.g., the Kujukuri beach survey). In addition, the sea effect was a function of the host rock resistivity. For example, if the host rock resistivity was 100 ohm-m, the effect of the sea on the EM field was larger than if the host rock resistivity was 10 or 1 ohm-m.

Keywords: Airborne EM, Sea effect, 3D resistivity modeling, GREATEM survey, Coastal areas survey.

INTRODUCTION

New applications of airborne electromagnetic (AEM) survey techniques have been introduced in engineering and environmental fields, particularly for studies involving active volcanoes. In addition, time-domain methods offer advantages such as greater investigative scope and detail as well as increased accuracy in the mapping of freshwater/saltwater boundaries. However, the coastal effect might mask underlying structures because of the rapid decrease in the landside response at late times. As a result, the real signal drops below the noise level and even the synthetic response cannot be accurately calculated to probe underlying structures.

Yang et al. (1999) used a joint inversion scheme to evaluate the long-term detection of possible changes in the spatial distribution of the freshwater/saltwater interface in the Pei-kang area in the central part of the west coast of Taiwan. They found that saltwater intrusion in coastal areas caused changes in the electrical properties of the pore water in the aquifers. Aquifers most affected by saltwater are located at depths of 20 to 60 m along the coast and banks of the Pei-kang and Po-tzu rivers.

Goldman et al. (2011) used the broadside db_z/dt of extensive multidimensional modeling and numerous offshore measurements to study the two-dimensional (2D) coastal effect on marine time-domain electromagnetic measurements. Their results demonstrated that the coastal effect only occurs if short offset landside arrays are used. In such cases, the sharp seacoast resistivity contrast acts as a magnifying glass for the resistive sub-seafloor target. This coastal effect is most suitable for applications within a limited range of offsets, between approximately 40 and 80 m. Furthermore, at shorter offsets the measured signals exhibit sign reversals making the data less suitable for quantitative interpretation. The effect gradually disappears with larger offsets as well as with increasing distance from the coast. Depending on the offsets and depths to the target, the maximum distance from the coast varies from a few to several kilometers offshore.

A resistivity structure with a horizontally layered structure might be distorted in the case of large resistivity contrasts, such as between land and sea in coastal areas and between the air and topographic features considered as anomalies in the air layer. To overcome these issues we used three-dimensional (3D) electromagnetic (EM) numerical modeling utilizing a staggered-grid finite-difference method developed by Fomenko and Mogi (2002) to study the effects of both sea and topography on EM field induction by GREATEM survey systems.

THREE-DIEMENSION MODELLING THEORY

The 3D EM forward-algorithm used in this study draws on a staggered-grid finite-difference method developed by Fomenko and Mogi (2002) that involves the special pre-whitening of a large matrix to the improve the stability of computation and a devised solver. It is designed for computer calculation of the electrical (E) and magnetic (H) field components resulting from secondary EM fields originating from 3D anomalies inducing the primary EM field on a horizontal multi-layer structure. This approach is used to improve the accuracy of models with a high resistivity contrast over a wider frequency range. To apply it to a GREATEM study, we added a source term of a grounded electrical dipole source. The analytical expressions for the E and H fields by the electrical finite length source for a horizontal multi-layer condition were reported by Ward and Hohmann (1988). Time-domain EM responses were computed by the sine or cosine transformation from the frequency-domain data. The range of computing in the frequency domain is 10^5 to 10^{-2} Hz and transient time responses were obtained at 10^{-4} to 1 sec.

MODEL DESCREPTIONS AND REULTS

1. Sea-land boundary model

As shown in Figure 1, the sea-land boundary model consisted of two adjacent layers of different conductivity, where the sea was a thin sheet conductor (3.3 S/m) placed on top of a uniform half-space earth medium (0.01 S/m). The 3D modeling area was X: (-20 km, 15 km), Y: (-20 km, 20.4 km), and Z: (-12.2 km, 12 km). The model was composed of 40 x 29 x 28 = 32,480 cells. The node spacing was small near the source (50 m) and gradually coarsened with increased distance from the source in a horizontal direction. In the vertical direction, the size of each grid varied from 5 m at the surface to 3200 m at the top and bottom of the model. The EM responses were calculated for different positions of the grounded electrical source (at 10, 20, and 300 m) from the coastline landward, and the uniform half-space earth medium resistivity varied from resistive host rock (0.01 S/m) to highly conductive host rock (1 S/m). The flight altitude for modeling computation was 100 m.

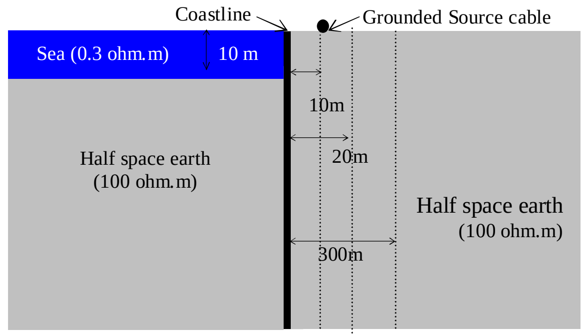

Figure 1. The sea-land boundary model. The sea is a thin layer (10 m depth) with conductivity of 3.3 S/m placed on top of a uniform half-space earth medium with conductivity of 0.01 S/m. The dipole sources are located 10, 20, and 300 m landward from the coastline (X =0 m).

1.1. Sea effect *vs.* the source position from coastline

Figure 2 shows the effect of the sea represented by the percentage difference in the response of the vertical magnetic field (in Hz) between the uniform half-space with or without sea for the three dipole source locations from the coastline (10, 20, and 300 m). As shown in the figure, if the dipole source position is located 10 m from the coastline, the effect of the sea on EM field induction is greater than if the dipole position is located 20 m or 300 m from the coastline. This indicates that the effect of the sea on EM induction is inversely proportional to the location of the source from the coastline.

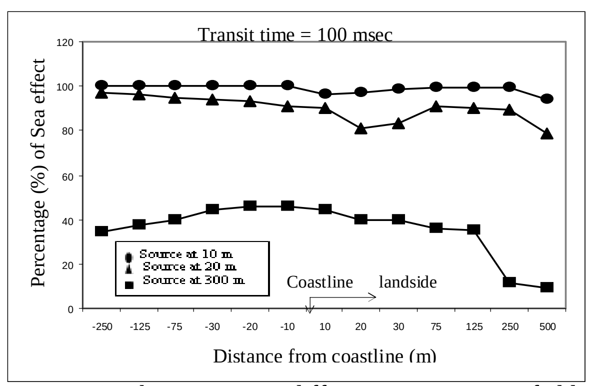

Figure .2. The percentage difference in magnetic field response between host rock (0.01S/m) with or without sea (3.3 S/m) for three source locations from the coastline (10, 20, and 300 m).

1.2. Sea effect *vs.* host rock conductivity

To study the relationship between the sea effect and host rock conductivity, we repeated the computation of the sea-land boundary model (Figure 1) with uniform half-space earth medium conductivities of 0.1 and 1 S/m instead of 0.01 S/m.

Figure 3 shows an example of the sea effect represented by the percentage difference in the response of the vertical magnetic field (in Hz) between the uniform half-space with or without sea for the three host rock conductivities (0.01, 0.1, and 1 S/m) with the source located 10 m from the coastline. The effect of the sea on EM field induction is greater for a host rock conductivity of 0.01 S/m than for host rock conductivities of 0.1 and 1 S/m. This indicates that the effect of the sea on EM induction is inversely proportional to the host rock conductivity.

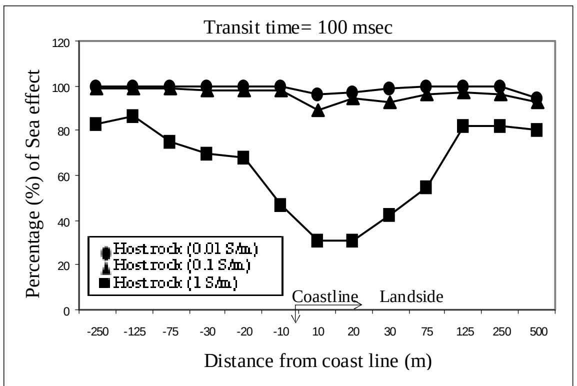

Figure.3. The percentage difference in vertical magnetic field response between host rock with or without sea for three host rock conductivities (0.01, 0.1, and 1 S/m). The source position is 10 m from the coastline.

2. Topography model

Topography in our model was represented as an anomaly (10^{-8} S/m) in the air layer. We selected a 3D-topographic model consisting of a topographic feature (10^{-2} S/m) placed on top of a uniform half-space earth medium (10^{-3} S/m) as shown in Figure 4.

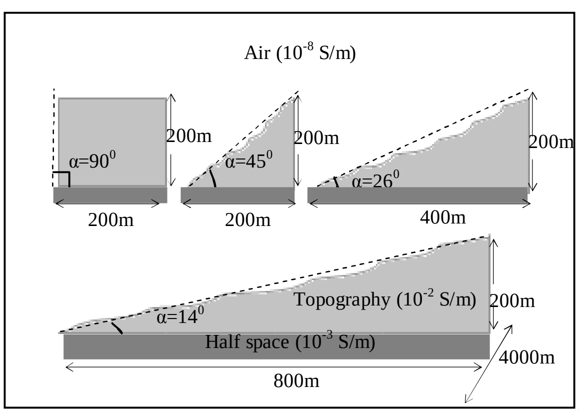

Figure.4. The 3D topography models. Topography (10^{-2} S/m) with different slope angles (α) placed on top of a uniform half-space earth medium (10^{-3} S/m).

The resistivity contrast was 10^6 times between the air and the topography. In the topographic area we used X: 50 x Y: 50 x Z: 25 m cells. Outside the topographic area, irregular cells were used. The total number of nodes was 52 x 38 x 32 = 63232 cells. The computations was done for four topographic slope angles (α) = 90^0 [topography width is 200m (x = 0 – 200m) and its height is 200m], (α) = 45^0 [topography width is 200m (x = 0 – 200m) and its height is 200m], (α) = 26^0 [topography width is 400m (x = 0 – 400m) and its height is 200m] and (α) = 14^0 [topography width is 800m (x = 0 – 800m) and its height is 200m]. In the four cases, the topography width in y–direction is 4000m (y = -2000 – 2000m), as shown in Figure 4. A horizontal electric dipole source was directed along the y-axis situated at the origin (x = -1500).

2.1. Topography effect on EM field induction

Figure 5 shows a comparison of the EM response between the topographic slope angles of 14° and 45° with the response of the uniform half-space earth medium at different flight altitudes (H). At a low flight altitude of 50 m, topography has a high significant effect on the EM response, which gradually decreases with increased flight altitude. Furthermore, a topographic slope angle of 45° showed a greater effect than a slope angle of 14°.

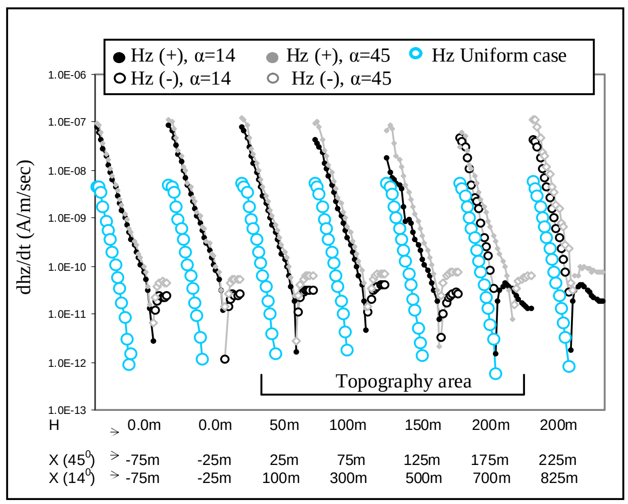

Figure.5. A comparison of the EM response between topography with slope angles of 14° and 45° and a uniform half-space earth medium at different flight altitudes (H).

Figure 6 shows the effect of topography represented by the percentage difference in the response of the vertical magnetic field (in Hz) between the uniform half-space with or without topography for topographic slope angles 90°, 45°, 26° and 14° at different flight altitudes. The effect of topography is most significant for a steep slope angle (90°) than for shallower slopes. Although the effect of topography can be observed for several meters on both sides of the topographic area, the side closer to the dipole source has a greater effect.

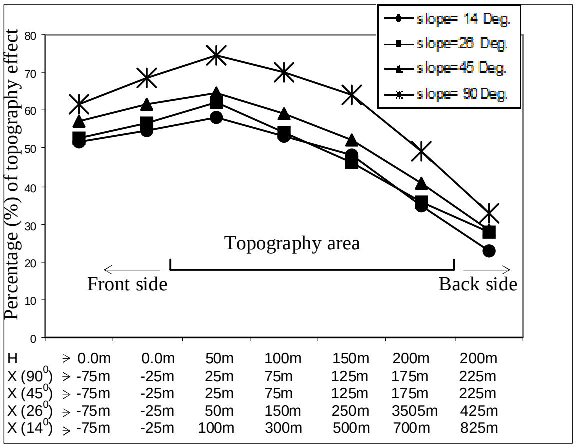

Figure.6. The percentage difference in the vertical magnetic field response between host rock with or without topography for four topographic slope angles (90°, 45°, 26°, and 14°) at different flight altitudes (H).

DISCUSSION

The 3D modeling results of the present study showed the following:

1. The sea effect on EM field induction at sea-land boundaries using GREATEM surveys depends on the position of the ground electrical dipole source relative to the coastline. For example, the coast effect when the source is located 10 m or 20 m landward from the coastline is greater than when the source is 300 m from the coastline. The sea effect also depends on the host rock resistivity. For example, if the host rock resistivity is 100 ohm-m, the effect of the sea on EM field induction is higher than if the host resistivity is 10 and 1 ohm-m.
2. The most significant effect of topography on EM field induction occurs at low flight altitudes and gradually decreases with increasing the flight altitude. The topographic effect of steep slope angles (e.g., 90° and 45°) is higher than for gentler slopes (e.g., 26° and 14°).

CONCLUSIONS

The sea effect on EM field induction by the GREATEM survey system is inversely proportional to both the distance of the dipole source from the coastline and the host rock conductivity. Topography with high slope angles has a greater effect than topography with low slope angles. In addition, the area of the topographic feature closer to the dipole source has a larger effect on EM field induction for several meters. The modeling results of this study will be considered when planning future GREATEM surveys as well as for the reasonable interpretation of data collected in coastal areas. Although it is encouraging that more studies of the sea effect are supported by quantitative modeling, the non-uniqueness of EM interpretation is a persistent problem and modeling still has to rely heavily on an obvious presumed structure.

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