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**A three-dimensional Resistivity Structure Study
Using Airborne Electromagnetics: Application
to GRETEM Field Survey Data.**

By

Abdallah Sabry Abdelmohsen Mohammed

Submitted for the Degree of Doctor of Philosophy

Dept. Natural History Science,

Graduate school of Science, Hokkaido University

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ABSTRACT

Applications of airborne electromagnetic (AEM) survey techniques have been introduced for environmental protection and natural disaster prevention in various fields. The objective of this study was to establish a method of constructing a three-dimensional (3-D) subsurface electrical resistivity model for a complicated structure using AEM data. Numerical forward modeling was performed using a modified staggered-grid finite-difference (SFD) method, and adding a finite-length electrical-dipole (FED) source routine to generate 3-D resistivity structure models of grounded electrical-source airborne transient electromagnetic (GREATEM) field survey data.

The GREATEM system was introduced by Mogi *et al.* (1998, 2009) and uses a grounded electrical dipole source of 2- to 3-km length as a transmitter and a three-component magnetometer in the towed bird as a detector. With a grounded source, a large-moment source can be applied and a long transmitter-receiver distance can be used to yield a greater depth of investigation, although the survey area becomes limited. Other advantages include a smaller effect of flight altitude and the possibility of higher-altitude measurements. Data are recorded in the time domain, providing a raw time series of the magnetic fields induced by eddy currents in the ground after cutting off the transmitting current, with the result that a noise filter can be easily introduced.

I have verified our 3-D electromagnetic (EM) modeling computing scheme, which is based on the SFD method (Fomenko and Mogi, 2002) by comparing the results of a quarter-space and trapezoidal hill models with the results of the 2.5-D finite-element method by Mitsuhashi (2000), and the 3-D finite-difference program with the spectral Lanczos decomposition method developed by Druskin and Knizhnerman (1994). This method was then used to study the possibility of detecting a conductor under shallower sea, the effects of sea and topographic features.

A 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 to 350 m both on land and offshore, in areas where low-resistivity structures are dominant. Another GREATEM survey was performed at a location in northwestern Awaji Island, where granitic rocks and paleogene sedimentary rocks crop out onshore. Resistivity structures at depths of 1 km

onshore and 500 m offshore were revealed by this survey. I performed numerical forward modeling using a modified SFD method by adding a FED source routine to generate a 3-D resistivity structure model from GREATEM field survey data at both Kujukuri beach and the Nojima fault.

Finally, I have confirmed the accuracy of our 3-D forward modeling computing scheme and evaluated the effects of complicated structures, such as sea or topography, on GREATEM data. I have used this method to generate a 3-D resistivity model from GREATEM field survey data acquired at the Kujukuri beach and the Nojima fault. As for results, I have obtained information regarding seawater invasion area in sedimentary rocks and a resistivity structure along an active fault. This study indicates that the GREATEM system can be used for the assessment of natural disaster areas.

Table of Content

Abstract	I
Table of Content	III
List of Figures	VI
List of Tables	XI
Acknowledgments	XII
Chapter 1 Introduction	1
1.1. Airborne Electromagnetics (AEM) Surveys	1
1.1.1. AEM History Overview	1
1.1.2. Traditional AEM Issues	2
1.1.3. Can GREATEM Solve the Problem?	3
1.1.4. Why Three-dimensional Modeling Is Needed	3
1.2. Outline of the Thesis.	4
Chapter 2 GREATEM System's Fundamentals and specifications	7
2.1. The GREATEM System	7
2.2. Measuring Equipment Specifications	8
2.3. Data Processing	13
2.3.1. Movement Correction	13
2.3.2. Coordinate Transformation	13
2.3.3. Removal of Local Noise	13
2.4. Inversion of Assumed Layer Structure	14
2.4.1. Correction of Instrument Frequency Response	14
2.4.2. Theoretical Analysis	16
2.5. Comparison between GREATEM and Other Conventional AEM	17
Chapter 3 Three-dimensional Electromagnetic Modeling of Sea and Topographic Effects on GREATEM Survey Data	19
3.1. Introduction	19
3.2. Three-dimension Forward Modeling Theory	19
3.3. Verification of the Forward Computing Algorithm	22

3.3.1. Quarter-space Model	22
3.3.2. Trapezoidal Hill with a Conductive Block Model	24
3.4. Model Descriptions and Results	25
3.4.1. Sea-land Boundary Model	25
3.4.2. Comparison of Sea Effect and the Source Position from Shoreline	26
3.4.3. Comparison of Sea Effect and Host Rock Resistivity	29
3.4.4. Topography Model	31
3.5. Results Summary	33
3.6. Conclusions	34
Chapter 4 Three-dimensional Resistivity Modeling of a Coastal Area Using GRETEM Survey Data from Kujukuri Beach, Chiba, Central Japan	35
4.1. Introduction	35
4.2. Survey Area	37
4.3. Data Acquisition	39
4.4. Data Processing	39
4.5. One-dimensional Inversion Results	39
4.6. Three-dimensional Modeling of GRETEM Field Data at Kujukuri Beach	40
4.7. Three-dimensional Synthetic Modeling Results	43
4.8. Comparison of 1-D and 3-D Resistivity Models	45
4.9. Discussion	47
4.10. Conclusions	49
Chapter 5 Three-dimensional Resistivity Modeling of GRETEM Survey Data from the Nojima Fault, Awaji Island, Hyogo, Southwest Japan	51
5.1. Introduction	51

5.2. Survey Area Description	é é é é .é é .é ...é é é é é é é é é ..é é é	.52
5.3. Previous Geophysical Studies	é é é é é ..é é ...é é é é é ...é é é é	...52
5.4. Data Acquisition	é é é é é é é é é é ...é é é é é ...é é é é é é é é	54
5.5. Data Processing	é é é é é é é ...é é é ..é é é é é é é é é .é é .é	...55
5.6. One-dimensional Inversion Results	é é é é é é é ..é .é é é é é ...é ..é	...56
5.7. Three-dimensional Modeling of GREATEM Nojima Field Data	é é é .é é	58
5.8. Three-dimensional Synthetic Modeling Results	é é é é é .é .é é é é .é é	.59
5.9. Comparison of 1-D and 3-D Resistivity Models	é é é é é é é é é é .é	62
5.10. Discussion	é é é é é é é é é é é é é .é é é é é é é é .é é é	..64
5.11. Conclusions	..é é é é é é é é é ...é é é é é é é é é é .é é	67
Chapter 6 Summary and Future Plans	é ..é é é é é .é é é .é é é	...69
List of Related Publications	é é é é .é é é é é é é é ...é .é é .é é	.72
References	é é é .é é é é é é ..é é ..é é é é é é é .é é é é .é	..74

List of Figures

Figure 2.1. Overview of the GREATEM system. The towed bird contained the three-component magnetometer, gyro, directional MI sensor, and GPS sensor. The data logger had a 16-bit AD converter, SSD memory, and a high-precision clock synchronized with the transmitter-control clock in the towed container. The secondary magnetic field induced in accordance with the ground resistivity was recorded during current on and off times.

Figure 2.2. Schematic diagram showing the GREATEM Airborne EM system.

Figure 2.3. Schematic diagram showing the data acquisition system [Air SEM].

Figure 2.4. Flow chart of the data processing: (A) example of a raw waveform, (B) three-component time-domain magnetic field data. Lines denote the data before (green) and after (red) motion correction. (C) enlarged resolution of the magnetic fields after motion correction, (D) Signal after 12th stacking, (E) Signal after 24th stacking and (F) an example of a final noise-free signal after determination of zero level.

Figure 2.5. Comparison of the frequency characteristic of instruments when the power is switched on (under primary field) / switched off (no primary field).

Figure.2.6..The 1-D inversion comparison of transient field data (red circles) and the calculated, layered-model transient curve (blue line).

Figure 2.7. Schematic diagram showing a comparison between GREATEM and conventional AEM systems. (After Verma *et al.*, [2013].)

Figure 3.1. A staggered grid cell V (i , j , and k). Tangential electric and normal magnetic field components are sampled at the center of edges (E) and at the center of interfaces (H), all of them continuous. φ_i , φ_j , and φ_k denote the sizes of the cells (after Fomenko and Mogi, 2002).

Figure 3.2. A quarter-space model. The Earth is divided by a vertical fault at $x = 0$ m. A y -directed horizontal electrical dipole (HED) source is situated on the left side of the contact. Four receiver sites are situated around the contact. (Modified from Mitsuhashi [2000].)

Figure.3.3. (A), (B), (C), and (D) are comparisons of the time derivatives of vertical magnetic fields (hz) obtained from the 3-D SFD, FEM 2.5-D, and SLDM 3-D

modeling code for the quarter-space model (Figure 3.2) at the four measuring points ($x = -750, -250, 250, \text{ and } 750 \text{ m}$). The analytical solutions for a homogeneous half-space of 1 q-m are shown together. The (+) and (i) signs indicate the response. (Modified from Mitsuhata [2000].)

Figure.3.4. A trapezoidal hill with a conductive block of 1 q-m . A y-directed HED source is located on the Earth surface at $x = 0 \text{ m}$. The center of the hill is at $x = 2000 \text{ m}$. The conductive block is situated between the source and the hill. Two receiver sites are on the hill and on the right side. (Modified from Mitsuhata [2000].)

Figure 3.5. Comparisons of the time derivatives of h_z obtained from 3-D SFD and FEM 2.5-D modeling code for the trapezoidal hill model of Figure 3.4 with/without a conductive block. The analytical solutions for a homogeneous half-space of 100 q-m are shown together. (Modified from Mitsuhata [2000].)

Figure.3.6. The sea-land boundary model. The sea is a thin layer (10-m depth) with a resistivity of 0.3 q-m placed on top of a uniform half-space Earth medium with a resistivity of 100 q-m . The dipole sources are located $10, 20, \text{ and } 300 \text{ m}$ landward from the shoreline ($x = 0 \text{ m}$).

Figure 3.7. A sketch of the grid cells used for the 3-D EM modeling in this study.

Figure.3.8. (A), (B), and (C) are comparisons of the time derivatives of dh_z/dt between half-space with sea (black)/without sea (blue) for three source positions from the shoreline ($10, 20, \text{ and } 300 \text{ m}$), respectively (Figure 3.6). (D) Percentage differences in the responses of dh_z/dt for the three cases shown in (A), (B), and (C).

Figure.3.9. (A), (B), and (C) are comparisons of the time derivatives of h_z between half-space with sea (black)/without sea (blue) in three cases of host rock ($100, 10, \text{ and } 1 \text{ q-m}$, respectively). (D) Percentage differences in the dh_z/dt response for the three cases shown in (A, B, and C). The source position is 10 m from the shoreline.

Figure 3.10. The 3-D topography models. Topography (100 q-m) with different slope angles (θ) placed on top of a uniform half-space Earth medium (100 q-m).

Figure 3.11. Comparison of the $d\text{hz}/dt$ responses among topography with slope angles ($\check{\text{U}}$) of 14° (black), 45° (gray), and a uniform half-space Earth medium (blue) at different ground levels (H). The transient time $T = 10^{-4}$ to 10^0 s.

Figure 3.12. The percentage differences in the $d\text{hz}/dt$ response between host rock with or without topography for four topographic slope angles ($\check{\text{U}} = 90, 45, 26, \text{ and } 14^\circ$) at different ground levels (H).

Figure 4.1. (A) Location of survey area in the Kujukuri coastal plain with 5-m bathymetric contours. White dots in (A) denote the places where current dipole electrodes were placed (modified from Ito et.al. 2011). (B) The study area on the Kujukuri coastal plain and flight lines. The thick brown line indicates the shoreline and the thick black line indicates the transmitter cable, which was placed ~ 300 m inland ($x=0.0$ m) and parallel to the shoreline ($x=300$ m). Meaningful data were obtained on flight lines with thicker color. The thicker dots on the flight lines indicate places where clear transient responses used for modeling were obtained.

Figure 4.2. Northwest to southeast 1-D resistivity section along the K flight line (easting 200 m). (After Ito *et al.*, [2011].)

Figure 4.3. An example for fitting the transient response curves between observed field data and 3-D numerical model data at (A) flight line F (RMSE = 2%), (B) flight line K (RMSE = 3%), and (C) flight line C (RMSE = 5%).

Figure 4.4. Schematic of the 3-D resistivity structure model of the GREATEM data for Kujukuri beach. The red arrow indicates the shoreline which is ~ 400 m from the source. A-A1 is a resistivity profile of the 3-D model corresponding to the F flight line ($y=1200$ m), B-B1 is a resistivity profile of the 3-D model corresponding to the K flight line ($y=200$ m), and C- C1 is a resistivity profile of the 3-D model at $z= 350$ m.

Figure 4.5. Northwest to southeast cross-section of the 3-D model along the profile A-A1, as shown in figure 4.4.

Figure 4.6. Northwest to southeast cross-section of the 3-D model along the profile B-B1, as shown in figure 4.4.

Figure 4.7. Northwest to southeast cross-section of the 3-D resistivity model along the profile C-C1 at a depth of 350 m as shown in figure 4.4.

Figure 4.8. Northwest-southeast resistivity structure profiles along the K flight line ($y=200$ m), comparing (A) the 1-D inversion model (After Ito *et al.*, 2011) and (B) 3-D model. Color scale of 3-D model changed to fit the color scale used in Ito *et al.*, (2011).

Figure 4.9. Northwest-southeast resistivity structure profiles comparing (A) the results estimated by 2D inversion of AMT (Mitsuhata *et al.*, 2006) and (B) the GREATEM results along the K flight line ($y=200$ m), at Kujukuri beach area. Shore line is located at $x=0.0$ m. Color scale of 3-D model changed to fit the color scale used in Mitsuhata *et al.*, (2006).

Figure 4.10. Pore-water conductivity profile measured from core samples extracted from borehole drilled near the Kujukuri shoreline (after Kiyama and Marui, 1999). Modified from Mitsuhata *et al.*, (2006)

Figure 5.1. The geological map of Northern Awaji Island showing the active faults upon Awaji Island (modified from Murata A. *et al.* 2001). The red square shows the survey area in the present study.

Figure 5.2. The study area on Awaji Island. Red lines indicate flight lines. The thick purple line indicates the transmitter cable, which was placed 10~50 m inland from the shoreline. The J2 line indicates low-speed flight lines. T1 and T2 indicate tie lines with normal flight lines. The thicker dots on the flight lines indicate places where clear transient responses used for modeling were obtained.

Figure 5.3. Northwest-Southeast 1-D resistivity section along (a) flight line B and (b) flight line H. Black markers indicating the layers boundaries. (After Ito *et al.*, [2012].)

Figure 5.4. Northwest-Southeast 1-D resistivity section along the J flight lines comparing (a) the flight line J with a flight speed of 60 km/h and (b) the flight line J2 with a flight speed of 40 km/h. Black markers indicating the layers boundaries. (After Ito *et al.*, [2012].)

Figure 5.5. The initial model used for the 3-D EM numerical modeling computation. The model consist of two adjacent onshore and offshore layers of different conductivity, such that the sea of (10-40 m) depth is a high conductor (0.3 q-m) placed on top of a sedimentary rock of varied low resistivities, and assuming the

presence of topographic structure on the inland side placed on high resistivity granitic rocks.

Figure 5.6. Examples of fitting the transient response curves between observed field data and 3-D numerical model data at (A) flight line B (RMSE = 2%), (B) flight line H (RMSE = 3%), and (C) flight line E (RMSE = 5%).

Figure 5.7. Schematic of the 3-D resistivity structure model from the GREATEM data for the Nojima fault area. A-A' is a resistivity profile along the 3-D model corresponding to the flight line B, B-B' is a resistivity profile along the 3-D model corresponding to the flight line H. C-C', D-D', E-E' and F-F' are resistivity profiles along the 3-D model for different depth slices at $z = 0.0$ m (near surface), 100 m, 300 m and 500 m respectively.

Figure 5.8. Northwest-southeast cross section of the 3-D resistivity model, (a) along A-A' profile (Figure 5.7) which corresponding to flight line B and (b) B-B' profile (Figure 5.7) which corresponding to flight line H.

Figure 5.9. (A), (B), (C) and (D) are a Plan view of the 3-D resistivity model at different depth slices along the profiles C-C', D-D', E-E' and F-F' (Figure 5.7) at different depth slices at $z = 0.0$ m (near surface), 100 m, 300 m and 500 m respectively.

Figure 5.10. Northwest-southeast resistivity structure profiles along the B flight line comparing (A) the 1-D inversion model and (B) 3-D model.

Figure 5.11. Northwest-southeast resistivity structure profiles comparing (A) the results of CSAMT (Takakura *et al.*, 1996) and (B) the GREATEM results along the B flight line at Awaji Island. The black dashed line indicates the Nojima fault. Color scale of 3-D model changed to fit the color scale used in Takakura *et al.*, (2006).

Figure 5.12. Northwest-southeast resistivity structure profiles comparing (A) the results of CSAMT (Ikeda *et al.*, 2000) and (B) the GREATEM results along the B flight line at Awaji Island. Coast line is at $X = 0$ m. Color scale of 3-D model changed to fit the color scale used in Ikeda *et al.* (2000)

Figure 5.13. Results of the borehole electrical resistivity logging data obtained from well drilling close to Nojima fault area. (After Ikeda *et al.*, [2000].)

List of Tables

Table 1. The specification of equipment on the airborne electromagnetic survey system
(GREATEM)

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Chapter 1

Introduction

1.1. Airborne Electromagnetic (AEM) Surveys

1.1.1. AEM History Overview

At the beginning of this chapter, I provide a brief history of AEM after Palacky *et al.* (1991), Fountain (1998) and Thomson *et al.* (2007). After the Second World War, there was great demand for reconstruction of what war had ravaged using natural resources. Therefore, explorationists sought secure supplies in countries geographically and politically close to the United States with vast areas that were little explored, of which Canada was an obvious choice. These circumstances provided an incentive to develop a geophysical method for use in sparsely populated countries in which the climate is often harsh and frigid for part of the year.

These methods were designed to be applied quickly and effectively for deposits of strategic base metals, such as copper, lead, zinc, and nickel. Airborne magnetometer systems that developed from early wartime prototypes used in submarine detection became widely used in mineral exploration in Canada. The first attempt known to the authors to mount EM equipment in an aircraft was made in 1946 by Hans Lundberg. This consisted of two coils mounted inside the helicopter cabin, and was flown in northern Quebec and Ontario. However, conductors could be detected only by overflying at an altitude of 5 m. More successful AEM development was initiated in 1949 by Stanley Davidson, a geologist with Stanmac, Ltd. McPhar Geophysics, Ltd., has developed a portable ground EM system that was tested on frozen lakes, which proved that the concept was feasible. International Nickel of Canada (INCO) contracted with McPhar to design and build the world's first operational AEM system. The initial successful test flights of the Stanmac-McPhar fixed-wing AEM system in Canada during the summer of 1948 can nominally be called the birth of this branch of exploration geophysics.

The discovery of the Heath Steele deposit in New Brunswick, Canada, in 1954 because of an AEM survey was the catalyst for the development of additional AEM systems and the eventual application of AEM surveys worldwide. The aircraft used was a wooden-

skinned Anson with an onboard transmitter and receiver towed in a bird. The field area in New Brunswick, Canada, was an instant success.

In the early 1950s, many inventors in Canada and elsewhere attempted to meet the potential of a booming market, and at least 10 types of AEM system became operational before the decade was over. The decade from 1950 to 1960 can be considered the period of survey platform and system geometry development. In 1955, the first towed, rigid-beam helicopter system was introduced with a 6 m (20 ft) bird. By the end of that decade, most of the basic AEM system geometries in use today, fixed-wing and helicopter, had been developed, and, at the end of the decade, the first time-domain INPUT surveys were flown. AEM development had also taken the separate paths of rigid transmitter-receiver systems and large separation, towed bird systems, which still exist today. During the decade, the first semi-airborne passive transmitter system, AFMAG, was developed in Canada, and a ground transmitter system was used in the USSR.

The need to detect deeply buried conductors stimulated renewed activity in AEM design in the late 1970s. The successful INPUT was redesigned using digital technology (Lazenby and Becker, 1984) and is now being operated by the Questor survey under the name QUESTEM. Geotrex gave its new version the name GEOTEM. New-generation AEM systems using powerful transmitters and the latest in computer technology were tested in the early and mid 1980s in CORTAN (Collet L., 1983), and SWEEPEM (Best and Bremner, 1986).

1.1.2. Traditional AEM Issues

Challenges for using AEM surveys in exploration areas include such issues as the high cost of conducting the survey, which in most cases results in delay or cancellation; and safety, as using the AEM survey at low altitude represents a high risk to the survey team. Another issue is the need to increase the depth of penetration to detect deeper structures, especially in the case of the presence of conductor terrains such as saline surface water, which decreases the penetration depth of the AEM signal. Improvement of the data-processing techniques together with advanced AEM modeling and inversion increase the signal quality. New AEM exploration challenges will require platforms with greater

range, reliability, safety, and a multiple-system operation capability on a cost-effective basis.

1.1.3. Can GREATEM Solve the Problem?

Considering the challenges of AEM surveys and attempting to identify reliable solutions to AEM problems, Mogi *et al.* (1998) described the early stages of Grounded Electrical source Airborne Transient EM (GREATEM) system development and gave the system its acronym. The objective was to develop a lightweight heli-TEM system capable of probing depths of the order of a few kilometers below the surface of the Earth. Using a long-ground electrical source cable, a large transmitter moment that can energize deeper regions is obtained, and signal attenuation with height is negligible, enabling use of more safe flight altitudes.

Based on its advantages in comparison with other systems such as (Heli-TEM), and with further developments in system efficacy, such as increasing the transmitter moment and improving the data-processing techniques to enhance the signal-to-noise ratio, the GREATEM system can solve most AEM problems.

1.1.4. Why Three-dimensional Modeling Is Needed

Airborne electromagnetic data are often interpreted using one-dimensional (1-D) methods either by apparent resistivity transforms (e.g., Huang and Fraser, 2002), or conductivity depth transforms (e.g., Wolfgram and Karlik, 1995). Although 1-D methods are widespread in the interpretation of AEM surveys, they often fail to recover even simple three-dimensional (3-D) targets (e.g., Ellis, 1995 and Ellis, 1998). This is because 1-D methods place the conductivity model beneath the midpoint for each transmitter-receiver pair.

The time-domain-induced current system in a homogeneous half-space resembling a "smoke ring" blown by the transmitter, which moves outward, downward, and diminishes in amplitude with increasing time after the transmitter, is turned off. In a homogeneous half-space, the physical electrical field maximum moves outward from the transmitter loop edge at an angle of approximately $\pm 30^\circ$ with the surface. This well-known "smoke ring" concept (e.g., Nabighian, 1979; Reid and Macnae, 1998) implies that AEM sensitivity is usually offset from the transmitter-receiver pair's midpoint

rather than beneath it. As a result, 1-D methods recover the conductivity structures for each transmitter-receiver pair that are spatially misplaced in 3-D. One-dimensional conductivity models are often interpolated to produce a pseudo-3-D model over the survey area. Three-dimensional targets often manifest themselves with artifacts or distortion in pseudo-3-D models. To produce accurate images of the subsurface, 3-D inversion is required as the real geological formations are 3-D by nature.

1.2. Outline of the Thesis

In this study, I performed numerical forward modeling using a modified staggered-grid finite-difference (SFD) method by adding a finite-length electrical-dipole source routine to generate a 3-D resistivity structure model from the GREATEM field survey data at both Kujukuri beach, Chiba, central Japan, and the Nojima fault, Hyogo, southwest Japan. This thesis comprises six chapters, summarized as follows:

In chapter 1, I give an introduction comprising AEM history and known AEM issues in addition to the significance of 3-D modeling.

In chapter 2, I describe the fundamentals of the GREATEM system, the measuring equipment specifications, measuring conditions, and data processing flow chart.

In chapter 3, I verify our computing 3-D EM modeling scheme based on the SFD method (Fomenko and Mogi, 2002). I compare the results of a quarter-space and trapezoidal hill models with the results of the 2.5-D finite-element method (FEM) Mitsuhashi (2000) and the 3-D finite-difference program with the spectral Lanczos decomposition method (SLDM) developed by Druskin and Knizhnerman (1994). I use it to study the oceanic seawater effects on EM field induction when conducting GREATEM surveys along coastal areas with topographic features. The models consisted of two adjacent layers with different conductivities; the sea was modeled as a thin sheet of good conductor placed on top of a uniform half-space Earth medium. The EM responses were calculated for grounded electrical sources in different positions (10, 20, and 300 m) landward from the shoreline. The uniform half-space Earth medium resistivity varied from a resistive host rock (100 Ω -m) to a highly conductive host rock (1 Ω -m). The effects of the sea on GREATEM survey data depended on the position of the ground electrical source relative to the shoreline.

In chapter 4, I describe the results of the GREATEM system survey that was conducted over the Kujukuri coastal plain in central Japan to assess the system's ability to accurately describe the geological structure beneath shallow seawater. To obtain high-quality data with an optimized signal-to-noise ratio, a series of data-processing techniques were used to obtain the final transient response curves from the field survey data. These steps included movement correction, coordinate transformation, the removal of local noise, data stacking, and signal portion extraction. To add the frequency response of measuring equipment to modeled data, the latter were convolved with the measured system responses of the corresponding data set.

I performed numerical forward modeling to generate a 3-D resistivity structure model from the GREATEM data. This model was developed from an initial 1-D resistivity structure that was also inverted from the GREATEM field survey data. Mogi *et al.*, (2011) modified a 3-D electromagnetic forward-modeling scheme based on a finite-difference staggered-grid method and used it to calculate the response of the 3-D resistivity model along each survey line. I verified the model by examining the fit of the magnetic-transient responses between field data and the 3-D forward-model computed data. The inverted 3-D resistivity structures showed that the GREATEM system has the capability to map resistivity structures as far as 800 m offshore and as deep as 300–350 m underground in coastal areas of relatively shallow seawater depth (5–10 m).

In chapter 5, I describe the results of the GREATEM system survey that was conducted over the Nojima fault on Awaji Island, Hyogo, southwest Japan, to assess GREATEM survey applicability for studying coastal areas with complex topographic features. To obtain high-quality data with an optimized signal-to-noise ratio, a series of data-processing techniques was used to acquire the final transient response curves from the field survey data.

The 1-D inversion results were feasible in that the horizontal resistivity contrast was not much higher than the true contrast, but they were not reasonable in that the horizontal resistivity values were greatly changed. To circumvent this problem, I constructed a 3-D resistivity model based on an initial model consisting of two adjacent onshore and offshore layers of different conductivities, such that a highly conductive sea of depth (10–40 m) is placed on top of a uniform half-space, assuming the presence of topographic features on the inland side. I verified the model by examining the fit of

the magnetic-transient responses between field data and the 3-D forward-model computed data. The inverted 3-D resistivity structures showed that the GREATEM system has the capability to map underground resistivity structures as deep as 500 m onshore and offshore. The GREATEM survey delineated how seawater intrudes on the landside of the fault.

In chapter 6, I provide a general summary of the whole thesis and propose future research.

Chapter 2

GREATEM System's Fundamentals and Specifications

2.1. The GREATEM System

The GREATEM system was described in details by Mogi *et al.*, (2009) and Okazaki *et al.*, (2011), here I describe based on their description. The GREATEM uses a grounded electrical dipole source of 2-3 km length as a transmitter and a three-component magnetometer in the towed bird as a detector (Figure 2.1). With a grounded source, a large-moment source can be applied and a long transmitter-receiver distance used, yielding a greater depth of investigation but limiting the survey area. Other advantages include a smaller effect of flight altitude and the possibility of higher-altitude measurements.

Data are recorded in the time domain, providing raw time series of the magnetic fields induced by eddy currents in the ground after cutting off the transmitting current, meaning that a noise filter can be easily introduced. The GREATEM system is considered to be an airborne version of the Long Offset Transient Electromagnetics (LOTEM) system (Strack, 1992), one of the electromagnetic survey systems used in surveying deeper structures. Transient data acquisition in the time domain after cutting off the source current has advantages for deeper exploration because it avoids the near-field effect (Goldstein and Strangway, 1975) that is included in frequency-domain data.

Mogi *et al.* (1998) described the early stages of GREATEM system development and gave the system its acronym. In addition, they illustrated some theoretical transient responses of magnetic fields in the air for horizontally layered structures and noted several features of the GREATEM response, such as depth of investigation, effect of measuring height, and source-receiver distance. They also highlighted the system's advantages in investigating deeper structures and the possibility of identifying resistivity

structure responses from heights of 100-200 m. This is important for improving the safety of AEM surveys.

Although time-domain data stacking on a moving aircraft is limited, important technical problems must be overcome, such as monitoring and filtering motion noise in the data, cancelling natural magnetic field variation, and limiting cultural noise. A high-accuracy fiber-optic gyro (Japan Aviation Electronics Industry, JCS7401) to monitor the motion of the bird, and a magneto-impedance (MI) sensor (Mohri *et al.*, 2002) to monitor direction were both set on gimbals, and a three component induction-coil magnetometer was installed at the rear of the gimbal mount. These instruments and the batteries were placed in the bird, and the data-acquisition instruments, consisting of a data-control PC and a high-precision clock synchronized with the transmitter-control clock, were set up in the helicopter cabin. Recently, the data-acquisition equipment installed in the small container and it towed at 10m above the bird. Full time-series data were collected to facilitate the elimination of noise. The three-component time derivative of magnetic fields, motions detected by the roll, pitch, and three-axis acceleration systems, and direction and position were digitized at the rate of 80εsec using a 16-bit analog to digital (A/D) converter. An identical three-component coil on the ground monitored natural and cultural noise in the survey area.

2.2. Measuring Equipment Specifications

Figure 2.2, a schematic diagram showing the GREATEM Airborne EM. Transmitted current is interrupted using high-precision clock which is synchronized with the control clock in the data acquisition system. Transmitted waveform is +, 0, -, 0 form and each time interval is 0.4 sec in standard manner as shown in figure 2.1.

In order to decrease the contact resistance across the ground, the cable is trailed and snaked on both transmission source sides, and about 300 ground electrodes is installed in the ground in each side, so in two sides was installed about 600 steel bar electrodes. The current power to the ground is expected to be 20 - 30 A.

Received data are converted to digital form using an A/D converter with resolution of the 16 bit and a sampling rate at 80εsec. A 0.8 second half cycle of 10,000 pieces of data are obtained. The files are saved as a 1-cycle of 1.6 seconds. The receiving devices are mounted in the bird and towed from a helicopter with 40m long rope.

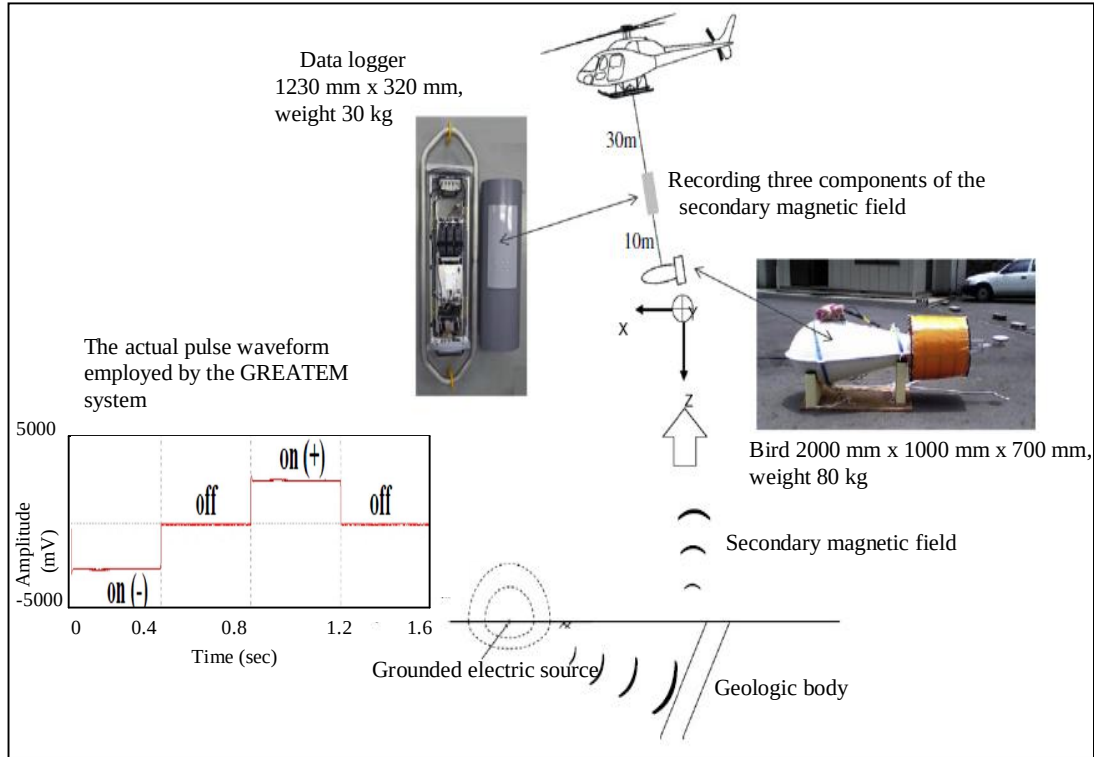


Figure 2.1. Overview of the GREATEM system. The towed bird contained the three-component magnetometer, gyro, directional MI sensor, and GPS sensor. The data logger had a 16-bit AD converter, SSD memory, and a high-precision clock synchronized with the transmitter-control clock in the towed container. The secondary magnetic field induced in accordance with the ground resistivity was recorded during current on and off times.

The data-acquisition system (Air SEM) which is composed of solid state drive (SSD) and analog to digital converter (A/D) that works at the rate of 80εsec is hung in the middle between the helicopter and the bird in order to avoid electrical noises as shown in figure 2.3.

Transmitted signal received at the current interruption using high-precision clock which synchronized with the transmitter-control clock in the container towed by helicopter. The three-component magnetic fields measured in the bird-fixed frame are converted into the geographical coordinate using the direction sensor mounted on the bird. The specification of above described instruments is shown in table 1.

The measured components X-component (north-N), Y-component (east-E) and Z-component (down). The flight Speed is about 50km/ h, and the flight attitude above ground is 50-150 m.

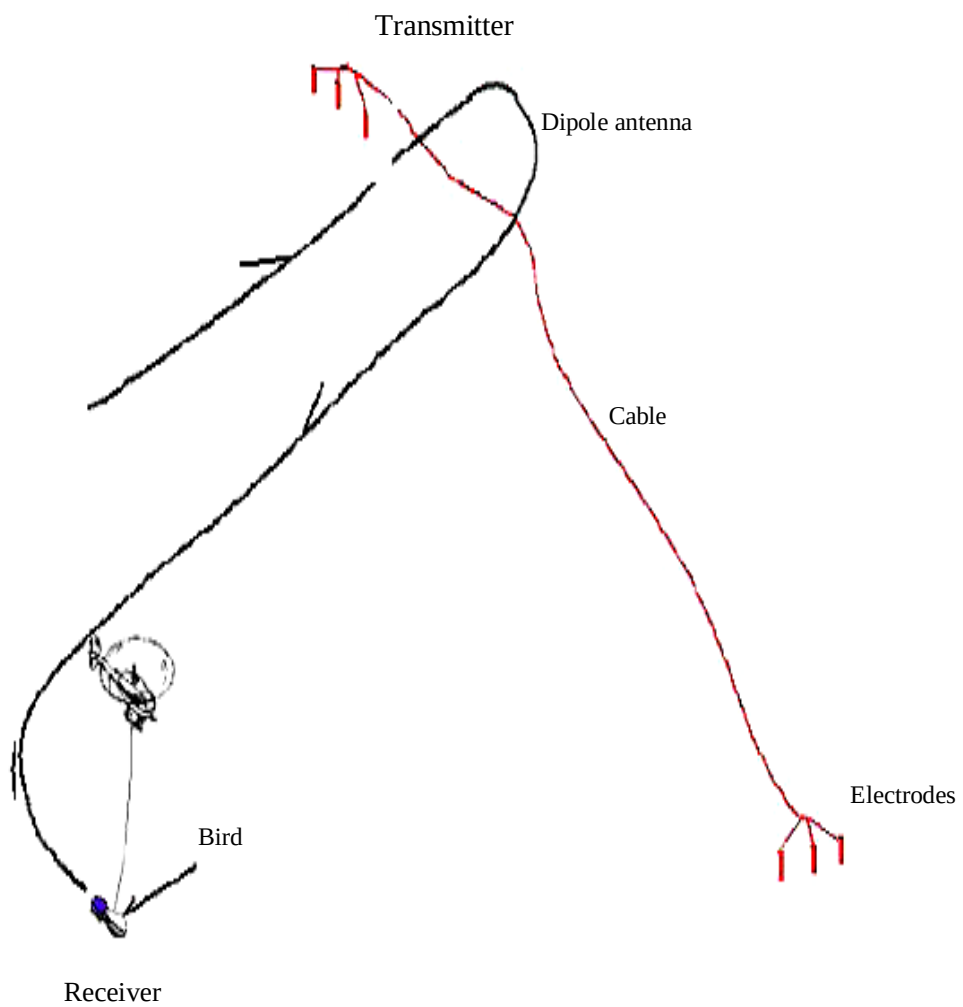
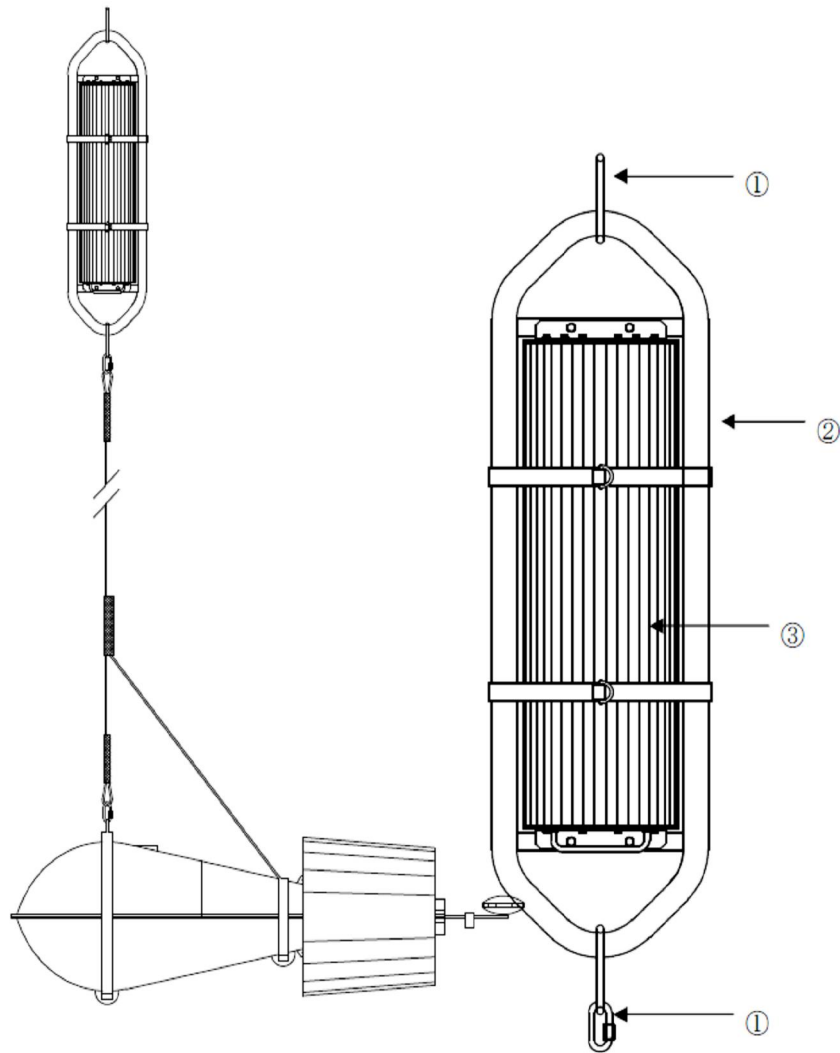


Figure 2.2. Schematic diagram showing the GREATEM Airborne EM



- ① ring for suspension of the bird,
- ② hanging frames (stainless steel pipe $\Phi 42.7$, length 1230mm, width 320mm)
- ③ data logger (cylindrical pipe made of PVC, Length 912mm, diameter 267mm, Gross weight 30kg)

Figure 2.3. Schematic diagram showing the data acquisition system [Air SEM].

Table 1. The specification of equipment on the airborne electromagnetic survey system (GREATEM)

Exploratory device	Name	Model Specifications
Airborne electromagnetic survey system	GREATEM	[Aerial Equipment Specifications] - Three components induction coil magnetic sensors - Fiber optic gyro type JCS-7401 - Directional detection sensor with MI sensor - Precision Clock (internal precision oscillator) - Novatel GPS-702 GPS Antenna - Novatel Prepak-G2-L1/L2 GPS receiver - Bird with FRP body, 40m long towing - Recorder (Resolution 16 bit [AirSEM])
		[Ground equipment specifications] - Three Phase, 440V, 60Hz and 25KW generator - Transmitter up to 25kw, 50A - Precision Clock (internal rubidium oscillator) - Current monitoring system (resolution 16bit) - Novatel GPS-702 GPS Antenna - Novatel Prepak-G2-L1/L2 GPS receiver
	Ground monitoring system	- Three components induction coil magnetic sensors - Precision Clock (internal rubidium oscillator) - Data acquisition system (resolution 16bit)

2.3. Data Processing

In the following section, I describe the advanced data-processing techniques performed to obtain a final transient response curve.

2.3.1. Movement Correction

Movement correction was performed using a transfer function relating variations in the recorded magnetic field to magnetometer movement, as monitored by the gyro. We used a highly accurate gyro to correct for the movement of the sensor. This correction was confirmed in previous surveys by Mogi *et al.* (2009) and Okazaki *et al.* (2011). The transfer function was calibrated at a time when no signal was applied. Corrections were made by subtracting predicted magnetic field variations using the transfer function based on the movement measured by the gyro from the observed magnetic field variations to yield data that were free from motion noise. Figure 2.4(A) shows an example of a raw waveform of received signal, and figure 2.4(B) shows an example of magnetic field data before (green lines) and after (red lines) the movement correction. Small transient responses remain but are clearly distinguishable in the motion-corrected time-series. The magnetic field data after movement correction at an increased resolution are shown in figure 2.4(C).

2.3.2. Coordinate Transformation

The transformation of magnetic field components from bird-based coordinates to geographical coordinates was based on the directional sensor data. The coordinate transformation correction was made using a tri-axis orthogonal coordinate transformation.

2.3.3. Removal of Local Noise

Magnetic field data obtained from the ground magnetometer were used to remove natural and artificial noise, as necessary. Multiple stacking provided the precise waveform induced by the transmitted signal at the ground-monitor site. The signature of local noise was incoherent because of the transmitter signal (TX) and airborne system movement. The noise involved in each set of time-series data was obtained by

subtracting the signal from each set of the monitored data, which was then subtracted from a set of concurrent airborne data.

When necessary, data stacking was used to minimize random noise. Because the helicopter was moving at 50 km/h, or 14 m/sec, the sensor moved about 22 m during one 1.6-sec cycle. A transient signal was present after the current cut-off twice in each cycle, so that one transient response could be inferred for each 11 m of survey distance. After stacking n times, the stacked data covered 11 n meters. Three to six transient signals were summed to reduce the noise waveform. Examples of signals after the 12th and 24th stackings are shown in figures 2.4(D) and 2.4(E), respectively.

2.4. Inversion for Assumed Layer Structure

2.4.1. Correction of Instrument Frequency Response

The received signals contain both of transmitted signals by the source and reflected ones by underground structure also the frequency characteristics of instruments. Considering the characteristics curve analysis of the instruments (Figure 2.5), if, the received signal (Y) at the instrument frequency response (G), and the subsurface response wave (X) in time domain, so

$$Y(t) = X(t) \times G(t) \quad (2.1)$$

where t is time and $\times$ is convolution multiples.

Therefore, after the transformation to the frequency domain, the frequency response of the subsurface response given by the following formula

$$X(\omega) = \frac{Y(\omega)}{G(\omega)} \quad (2.2)$$

where ω is the angular frequency. Finally, using inverse Fourier transform for $X(\omega)$, the time-domain wave $x(t)$ can be obtained. The obtained waveform $x(t)$ will be consistent with the resistivity structure.

This is normal method to remove system response of equipment from field data. But, deconvolution in Eq. (2.2) is unstable and affected much by noise. It is better to use a method that convoluted theoretical response with system response to subsurface response wave. Eq. (2.1) is using to structural analysis compared with field responses including system response.

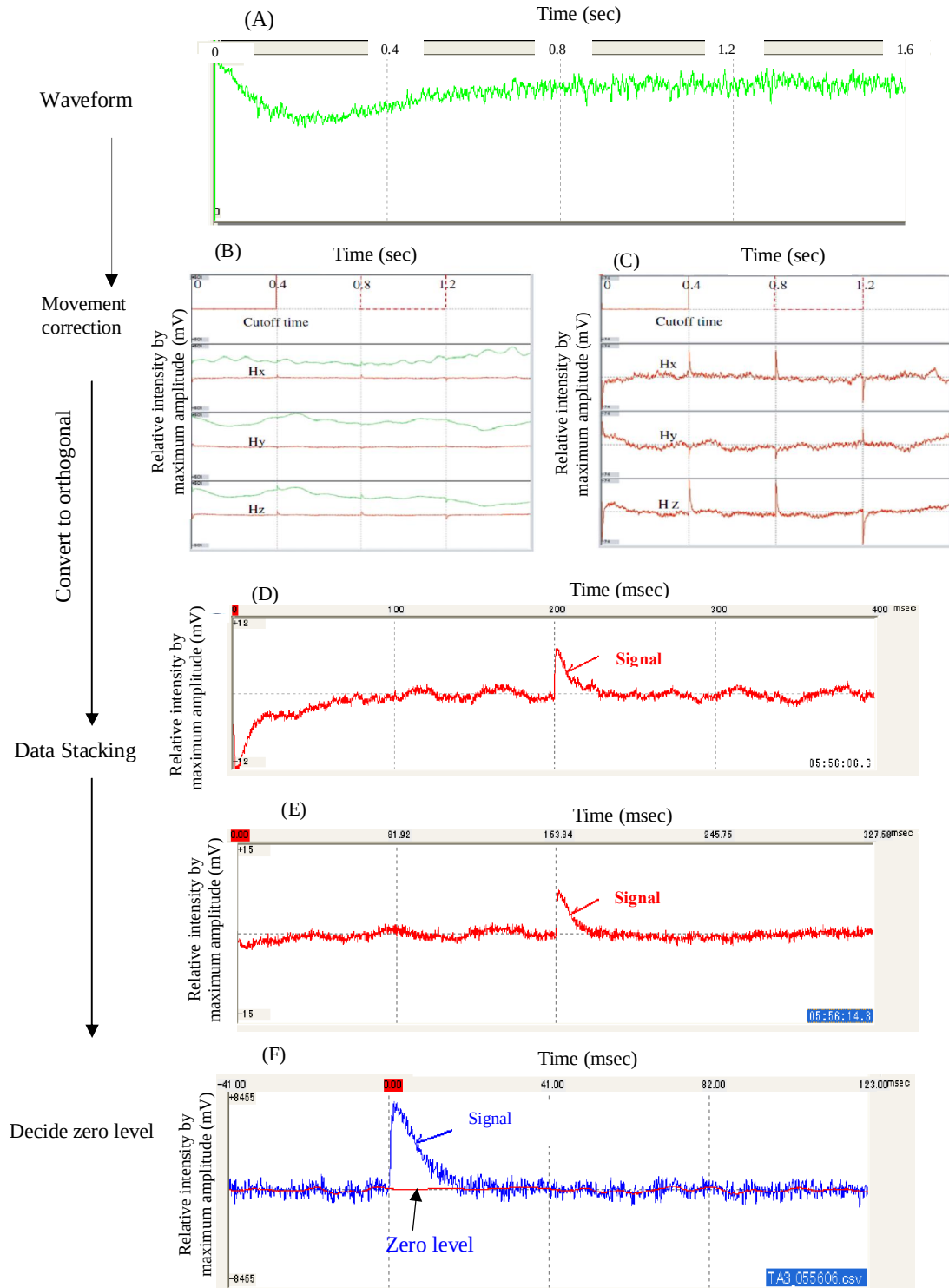


Figure 2.4. Flow chart of the data processing: (A) example of a raw waveform, (B) three-component time-domain magnetic field data. Lines denote the data before (green) and after (red) motion correction. (C) enlarged resolution of the magnetic fields after motion correction, (D) Signal after 12th stacking, (E) Signal after 24th stacking and (F) an example of a final noise-free signal after determination of zero level.

2.4.2. Theoretical Analysis

Usually, vertical component of the magnetic field (Hz) in frequency domain is used in analyzing subsurface structure, assuming the horizontally layered earth because responses are simpler and effect of natural noise is smaller than horizontal components. Using the basic theory of the transmission sources (small dipole source) in case of horizontal layered, (Ward and Hohmann, 1988; Spies and Frischknecht, 1991), the magnetic field is:

$$H_z = \frac{-P}{2\pi k^2 r^4} [3 - (3 + 3ikr - k^2 r^2)e^{-ikr}] \quad (2.3)$$

where P is electrical dipole moment, r is the transmitter-receiver separation and k is propagation constant or wave number for lower half space and given by

$$k = (-i\sigma\mu\omega)^{1/2} \quad (2.4)$$

where σ is the conductivity, μ the magnetic permeability and ω is the angular frequency. The solution is obtained in the frequency domain and it is necessary to convert from time-domain data using the inverse Fourier transformation.

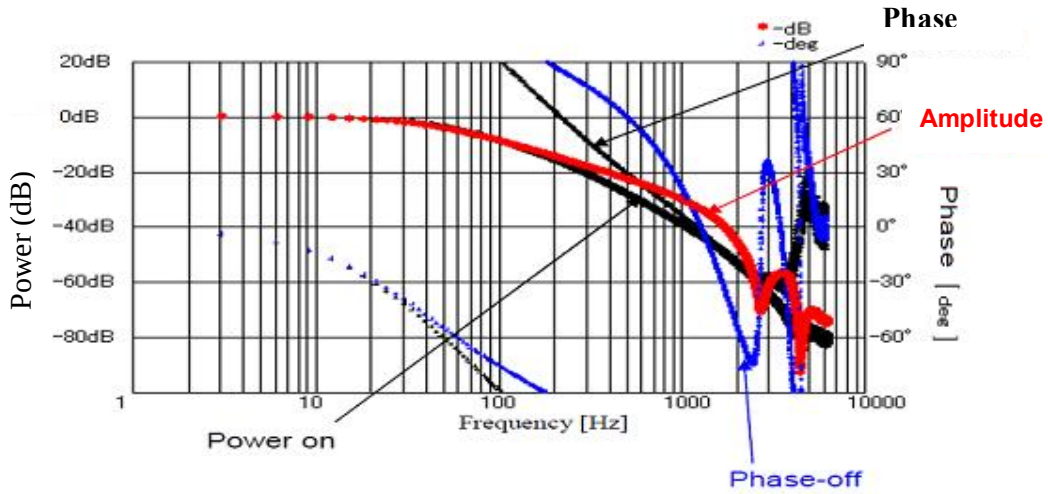


Figure 2.5. Comparison of the frequency characteristic of instruments when the power is switched on (under primary field) / switched off (no primary field)

After the previous data processing and corrections were made, the noise-free transient response $x(t)$ as shown in figure 2.4(F) was inverted to determine a 1-D resistivity structure. I used the part of the transient response with less dispersion due to noise and

abandoned the part of the transient curve contaminated with noise. The transient response curve of dhz/dt was used to model the waveform. The inversion was made by comparing field data with theoretical responses (Ward and Hohmann, 1988; Jomori, 1991) as shown in figure 2.6. Seven horizontal layers were assumed and a non-linear least-squares method (as in the study of Strack, 1992) was applied.

The depth of investigation is defined as the depth corresponding to the transient response time at which response data become difficult to fit to a theoretical curve due to scatter caused by noise.

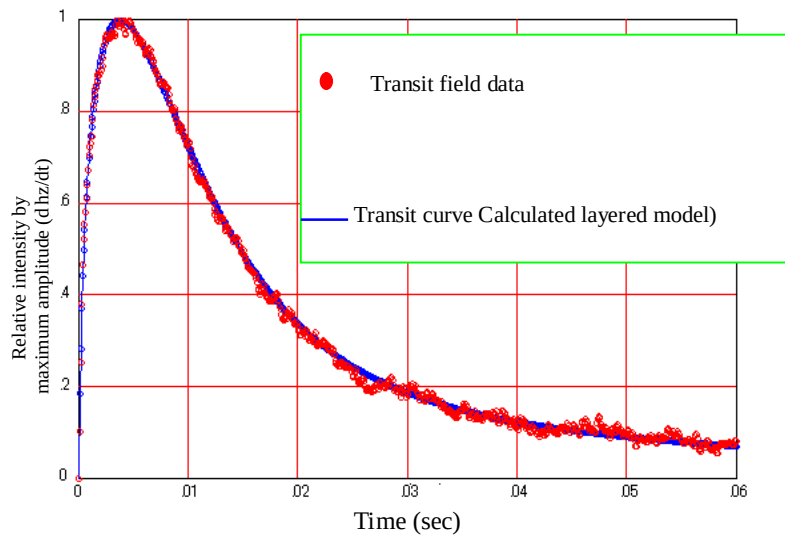


Figure 2.6. The 1-D inversion comparison of transient field data (red circles) and the calculated, layered-model transient curve (blue line).

2.5. Comparison between GRETEM and Other Conventional AEM

The GRETEM system's cable source is located on the ground and the pulse injected to the earth at a steady level, the changes in the response of the GRETEM system in respect of the LOTEM system (height = 0 m) are nominal. In contrast, the amplitude reduction with increase in the flight altitude is much sharper in conventional heli-TEM systems that fly the transmitter also, and the ground energization changes continuously along the flight line as well as with height.

With a grounded source, a large-moment source can be applied, and with a long transmitter-receiver distance, a greater depth of investigation can be achieved in a limited survey area. In addition, this greatly simplifies the helicopter logistics as only a

receiver bird is required to be flown below the helicopter⁽⁹⁾. Other advantages include, as the pulse directly inject to the earth by ground source, the amplitude reduction with flight altitude is not significant which enables the possibility of higher-altitude measurements around 100m or more. Thus the system is safer compared to a number of conventional heli-TEM systems that carry large and heavy under-slung transmitter loops (at times exceeding 30m in diameter and weighing more than 500kg) with terrain clearance of about 30m. Verma *et al* (2013) concluded that, in case of the conventional AEM systems that fly the transmitter AEM, the $\delta\tau$ images of a confined conductor (after Combrinck, 2011) remain at the same location as both, the transmitter and receiver move together over the body. Thus these systems map subsurface conductors locally as compared to the AEM systems that use grounded transmitter (e.g. GREATEM) that also maps the regional effects due to continuous energization of the earth by a stationary grounded transmitter. This could be particularly advantageous in structural or lithological mapping. Figure 2.7 shows the comparison of GREATEM with Conventional AEM systems (Verma *et al.*, 2013).

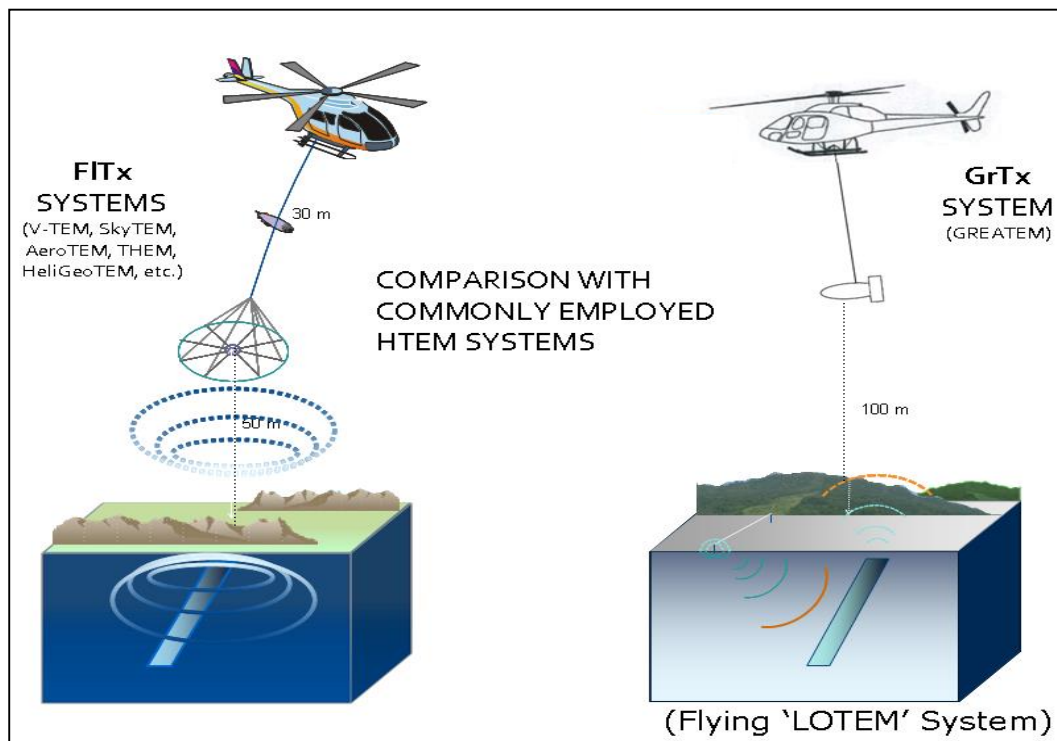


Figure 2.7. Schematic diagram showing a comparison between GREATEM and conventional AEM systems. (After Verma *et al.*, [2013].)

Chapter 3

Three-dimensional Electromagnetic Modeling of Sea and Topographic Effects on GREATEM Survey Data

3.1. Introduction

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, I used the 3-D EM numerical modeling utilizing a SFD method developed by Fomenko and Mogi (2002) to study the effects of both sea and topography on GREATEM survey data.

3.2. Three-dimension Forward Modeling Theory

The 3-D EM forward algorithm used in this study draws on the SFD method developed by Fomenko and Mogi (2002), which involves the special pre-whitening of a large matrix to 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, which are induced by the primary EM field in 3-D anomalies 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 modified this algorithm by adding a source term of a grounded electrical-dipole source (Mogi *et al.*, 2011). To compute a finite-length electrical-dipole source term, we used the formulae for a long grounded wire on a layered Earth described by Ward and Hohmann (1988), equations 4.184i 4.190 in their book.

Here, I describe the formulation of the SFD method after Fomenko and Mogi (2002). The time-domain EM responses were computed by 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 10^0 s. In forward modeling, the second-order partial differential equations for scalar and vector potential are discretized on a SFD method (after Fomenko and Mogi, 2002; Mogi *et al.*, 2011). Figure 3.1 shows the staggered grid cell used for this algorithm computation.

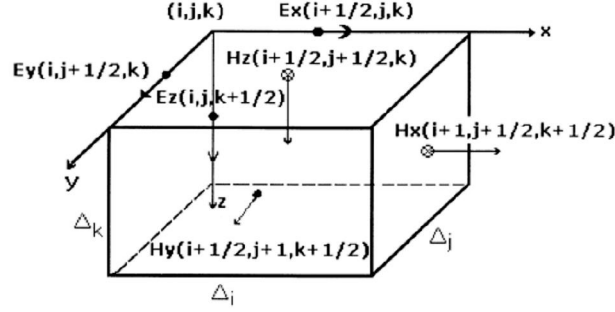


Figure 3.1. A staggered grid cell $V(i, j, \text{ and } k)$. Tangential electric and normal magnetic field components are sampled at the center of edges (E) and at the center of interfaces (H), all of them continuous. Δ_i , Δ_j , and Δ_k denote the sizes of the cells (after Fomenko and Mogi, 2002).

Assuming the time harmonic dependence $e^{i\omega t}$ (ω : angular frequency) and ignoring the displacement current in magnetotelluric modeling, Maxwell's equations for the total electric (E) and magnetic field (H) in a staggered grid lead to

$$\oint H dl' = \iint \sigma E ds' \quad (3.1)$$

$$\oint E dl = i\omega\mu \iint H ds \quad (3.2)$$

$$\oint_{dV_{ijk}} (\sigma E) ds = 0, \quad \text{or} \quad \text{div}(\sigma E) = 0 \quad (3.3)$$

$$\oint_{dV_{ijk}} (H) ds = 0, \quad \text{or} \quad \text{div}H = 0 \quad (3.4)$$

where μ is the magnetic permeability and σ is the conductivity distribution of the cells of a normal grid, ds correspond to the normal grid cells and ds' correspond to the central grid cells.

After SFD approximation of Eqs. (3.1) - (3.4) we obtain six scalar equations shown as (3.5 - 3.10)

$$\begin{aligned} & (H_{j+1/2}^z - H_{j-1/2}^z)\Delta_{k-1}' - (H_{k+1/2}^y - H_{k-1/2}^y)\Delta_{j-1}' \\ & = (\sigma)_{i,j-1,k-1}^x E_{i-1/2,j,k}^x \Delta_{j-1}' \Delta_{k-1}' \end{aligned} \quad (3.5)$$

$$\begin{aligned}
& (H_{k+1/2}^x - H_{k-1/2}^x) \Delta'_{i-1} - (H_{i+1/2}^z - H_{i-1/2}^z) \Delta'_{k-1} \\
& = (\sigma)_{i-1,j,k-1}^y E_{i,j-1/2,k}^y \Delta'_{k-1} \Delta'_{i-1}
\end{aligned} \tag{3.6}$$

$$\begin{aligned}
& (H_{i+1/2}^y - H_{i-1/2}^y) \Delta'_{j-1} - (H_{j+1/2}^x - H_{j-1/2}^x) \Delta'_{i-1} \\
& = (\sigma)_{i,j-1,k}^y E_{i,j,k-1/2}^z \Delta'_{i-1} \Delta'_{j-1}
\end{aligned} \tag{3.7}$$

$$\begin{aligned}
& (E_j^z - E_{j-1}^z) \Delta'_{k-1} - (E_k^y - E_{k-1}^y) \Delta'_{j-1} \\
& = i\omega\mu H_{i,j-1/2,k-1/2}^x \Delta_{j-1} \Delta_{k-1}
\end{aligned} \tag{3.8}$$

$$\begin{aligned}
& (E_k^x - E_{k-1}^x) \Delta'_{i-1} + (E_i^z - E_{i-1}^z) \Delta'_{k-1} \\
& = i\omega\mu H_{i-1/2,j,k-1/2}^y \Delta_{k-1} \Delta_{i-1}
\end{aligned} \tag{3.9}$$

$$\begin{aligned}
& (E_i^y - E_{i-1}^y) \Delta'_{j-1} + (E_j^x - E_{j-1}^x) \Delta'_{i-1} \\
& = i\omega\mu H_{i-1/2,j-1/2,k}^z \Delta_{i-1} \Delta_{j-1}
\end{aligned} \tag{3.10}$$

where for example,

$$\begin{aligned}
& (\sigma)_{i-1,j-1,k}^z = [\sigma_{i,j,k} \Delta_i \Delta_j + \sigma_{i-1,j,k} \Delta_{i-1} \Delta_j \\
& + \sigma_{i,j-1,k} \Delta_i \Delta_{j-1} \\
& + \sigma_{i-1,j-1,k} \Delta_{i-1} \Delta_{j-1}] / (4\Delta'_{i-1} \Delta'_{j-1})
\end{aligned} \tag{3.11}$$

The $\mathbf{H}$ field is calculated using the curl-operator in Eqs. (3.8-3.10). Tangential electric and normal magnetic field components are continuous at the staggered grid due to the selection of grid nodes. It helps to stably calculate the magnetic $\mathbf{H}_z$ component in the center of cell interfaces $\mathbf{X}_{i+1/2}$, $\mathbf{Y}_{j+1/2}$ at each level $\mathbf{Z} = \mathbf{Z}_k$ by using equation (3.10).

The original system describing Eqs. (3.5-3.10) is a pair of coupled first-order equations for $\mathbf{E}$ and $\mathbf{H}$. In order to decrease the number of equations, $\mathbf{H}$ -field eliminated from Eqs. (3.5-3.7) using the right-hand side of Eqs. (3.8-3.10), the second-order SFD equation was introduced as follows:

$$\tilde{A}(E^s + E^p) = \tilde{A}E^{total} = 0 \tag{3.12}$$

The matrix $\tilde{A}$ is neither Hermitian nor symmetric, but it can be transformed to the complex symmetric matrix $\hat{A}$ by multiplying the obtained equations by factor Δ_i for $\mathbf{E}^x$ members in the right side, Δ_j for $\mathbf{E}^y$ and Δ_k for $\mathbf{E}^z$.

3.3. Verification of the Forward Computing Algorithm

I have verified our 3-D electromagnetic (EM) modeling-computing scheme described previously. Verification is based on the 3-D modeling method by comparing the results of a quarter-space and trapezoidal hill models with the results of the 2.5-D finite-element method (FEM) by Mitsuhata (2000), and the 3-D finite-difference program with the spectral Lanczos decomposition method (SLDM) developed by Druskin and Knizhnerman (1994), which was described in Mitsuhata (2000). The models used to perform this verification were similar to that described by Mitsuhata (2000).

3.3.1. Quarter-space Model

The quarter-space model shown in Figure 3.2 consists of two quarter-spaces. On the left of the contact, the resistivity is 1 Ω -m, and on the right, 10 Ω -m. A horizontal electrical dipole (HED) source is directed to the y -axis and is situated on the surface at $x=-2250$ m to the left of the contact.

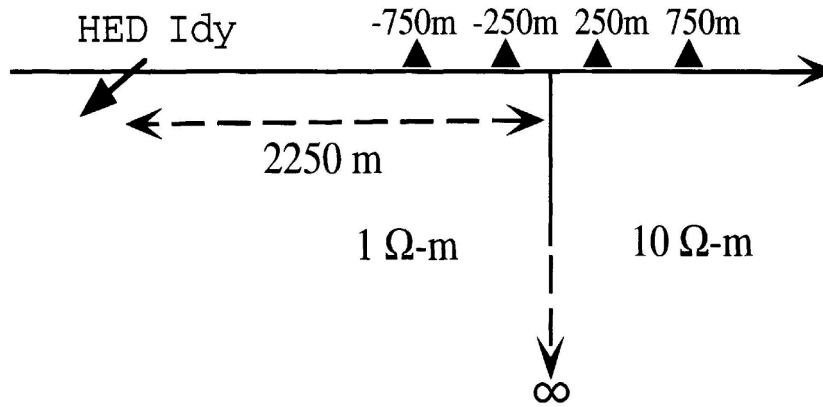


Figure 3.2. A quarter-space model. The Earth is divided by a vertical fault at $x = 0$ m. A y -directed horizontal electrical dipole (HED) source is situated on the left side of the contact. Four receiver sites are situated around the contact. (Modified from Mitsuhata [2000].)

Figure 3.3 shows the result in the time domain from 0.01 to 10 s at the sites near the contact. To check the validity of my computation method, the results of the time derivative of the vertical magnetic fields (Hz) obtained from 3-D SFD are compared with both of the results obtained by the 2.5-D FEM by Mitsuhata (2000) and the 3-D SLDM developed by Druskin and Knizhnerman (1994). Although minor differences exist, the main features of the three results are similar. At $x = -750$ m, the results are nearly equal to the analytical solutions for the homogeneous half-space of 1 Ω -m.

However, early time depressions begin to appear at $x = -250$ m. On the right side of the contact at $x = 250$ m, the depression becomes too strong and turns to a sign reversal. At $x = 750$ m, it becomes somewhat weak and the reversal disappears.

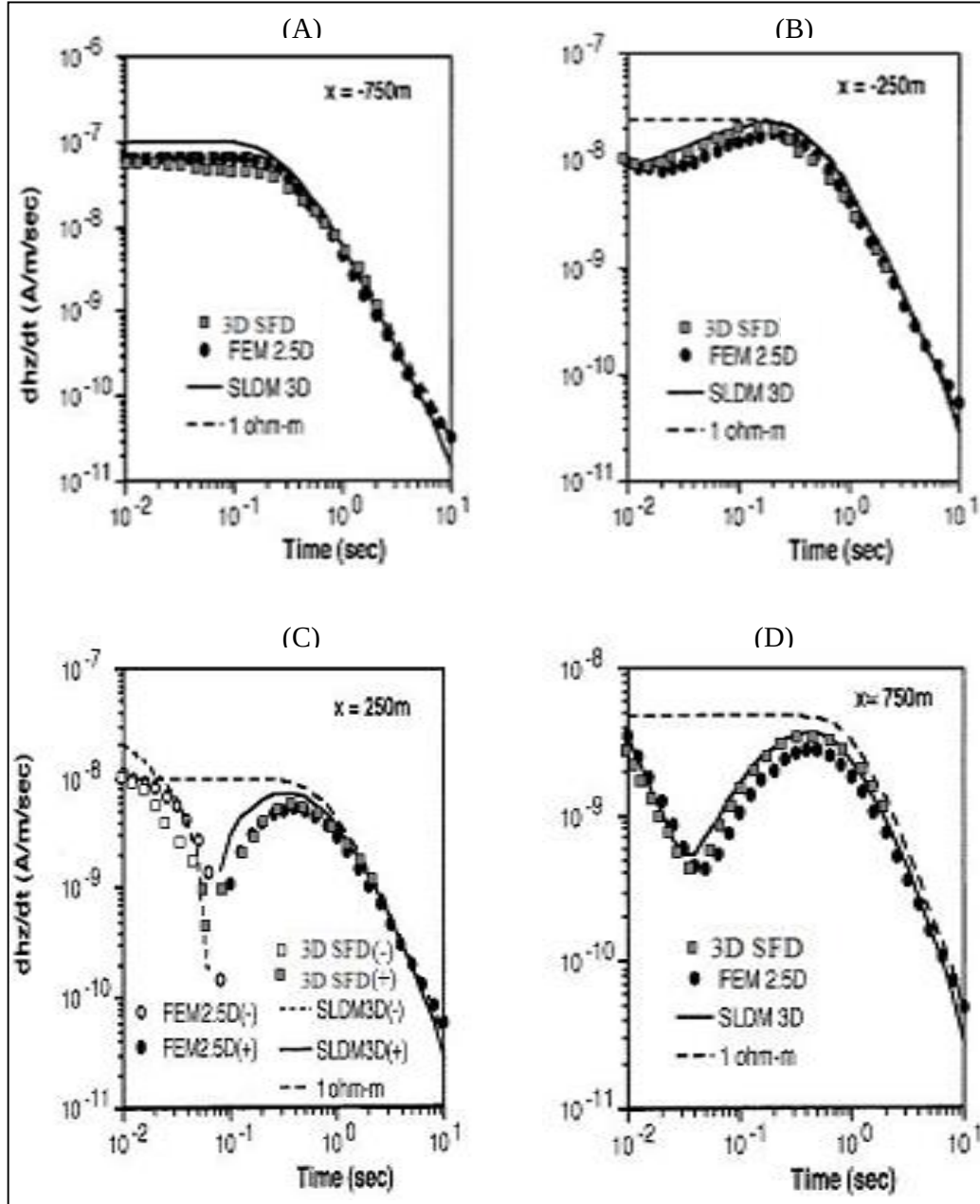


Figure.3.3. (A), (B), (C), and (D) are comparisons of the time derivatives of vertical magnetic fields (hz) obtained from the 3-D SFD, FEM 2.5-D, and SLDM 3-D modeling code for the quarter-space model (Figure 3.2) at the four measuring points ($x = \pm 750$, ± 250 , 250, and 750 m). The analytical solutions for a homogeneous half-space of 1 Ω -m are shown together. The (+) and (-) signs indicate the response. (Modified from Mitsuhashi [2000].)

3.3.2. Trapezoidal Hill with a Conductive Block Model

This model consists of a trapezoidal hill over a uniform 100 Ω -m half-space with an embedded conductive block of 1 Ω -m. A y-directed HED source is located on the Earth surface $x = 0$ m. The center of the hill is at $x = 2000$ m. The conductive block is situated between the source and the hill. Two receiver sites are on the hill at $x = 2000$ m and on the right side at $x = 6500$ m, as shown in Figure 3.4. The 3-D SFD used a rectangular grid, and a slope was modeled by tiers of grids.

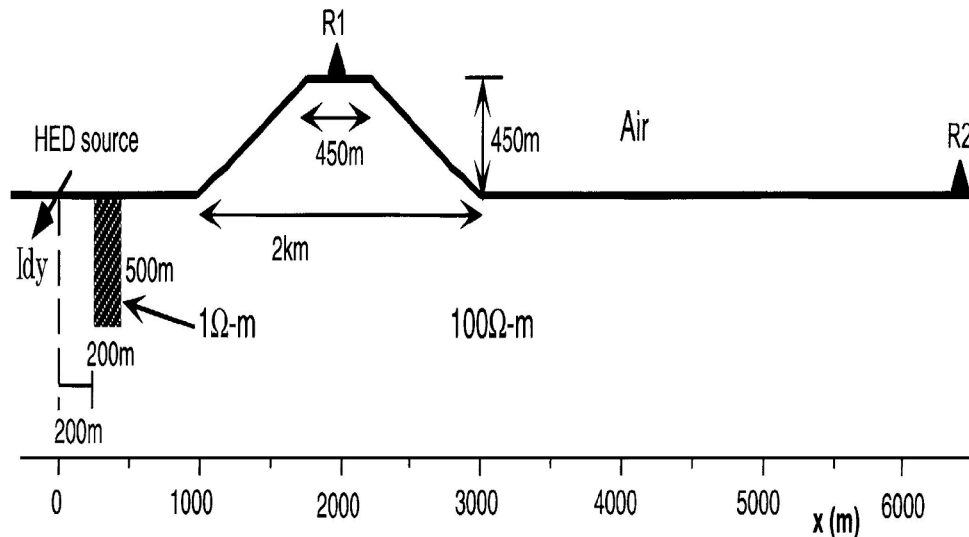


Figure.3.4. A trapezoidal hill with a conductive block of 1 Ω -m. A y-directed HED source is located on the Earth surface at $x = 0$ m. The center of the hill is at $x = 2000$ m. The conductive block is situated between the source and the hill. Two receiver sites are on the hill and on the right side. (Modified from Mitsuata [2000].)

Figure 3.5 shows comparisons of the time derivatives of hz response among the results obtained by 3-D SFD, those by 2.5-D FEM (Mitsuata, 2000), and the response of a flat homogeneous half-space of 100 Ω -m for reference. Although minor differences occur, the main features of these results are similar.

At both sites, the differences in the responses for the topographic model and homogeneous half-space are small. In contrast, the influence of the conductive block is significant. These results have verified the accuracy of our 3-D SFD computation algorithm and its viability for modeling complex structures and admitting interpretations

considering both topography and inhomogeneities located near the source and between the source and the receiver.

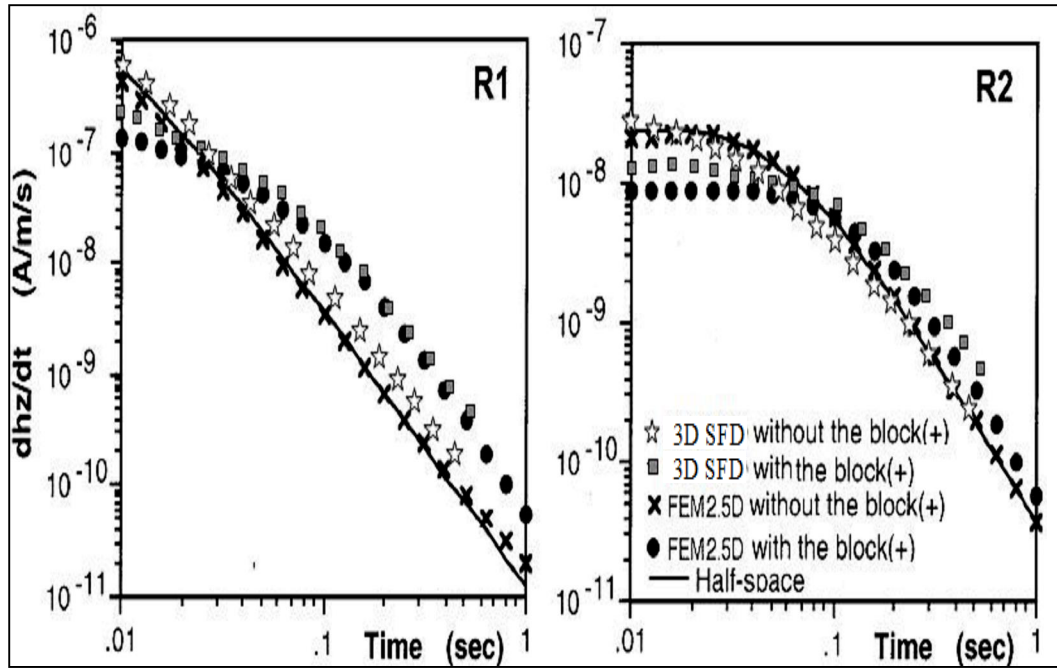


Figure 3.5. Comparisons of the time derivatives of h_z obtained from 3-D SFD and FEM 2.5-D modeling code for the trapezoidal hill model of Figure 3.4 with/without a conductive block. The analytical solutions for a homogeneous half-space of 100 q-m are shown together. (Modified from Mitsuhashi [2000].)

3.4. Model Descriptions and Results

3.4.1. Sea-land Boundary Model

As shown in Figure 3.6, the sea-land boundary model consisted of two adjacent layers of different conductivity, in which the sea was a thin-sheet conductor (0.3 q-m) placed on the top of a uniform half-space Earth medium (100 q-m). The 3-D modeling area was x : (120 km, 15 km), y : (120 km, 20.4 km), and z : (112.2 km, 12 km). The model was composed of $40 \times 29 \times 28 = 32,480$ cells.

The node spacing was small near the source (50 m) and gradually coarsened with increasing 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, as shown in Figure 3.7.

The EM responses were calculated for different positions of the grounded electrical source (at 10, 20, and 300 m) from the shoreline landward, and the uniform half-space

Earth medium resistivity varied from resistive host rock (100 q -m) to highly conductive host rock (1 q -m). The flight altitude for modeling computation was 100 m.

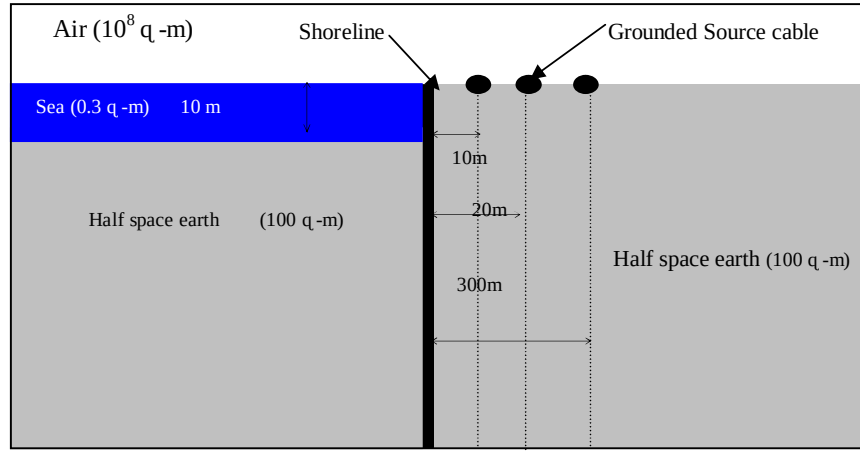


Figure.3.6. The sea-land boundary model. The sea is a thin layer (10-m depth) with a resistivity of 0.3 q -m placed on top of a uniform half-space Earth medium with a resistivity of 100 q -m. The dipole sources are located 10, 20, and 300 m landward from the shoreline ($x = 0$ m).

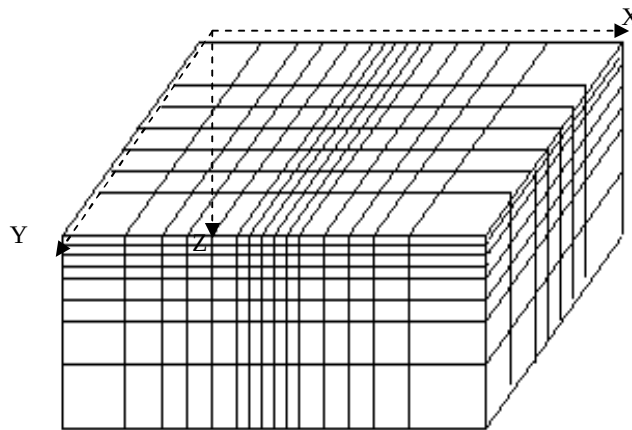


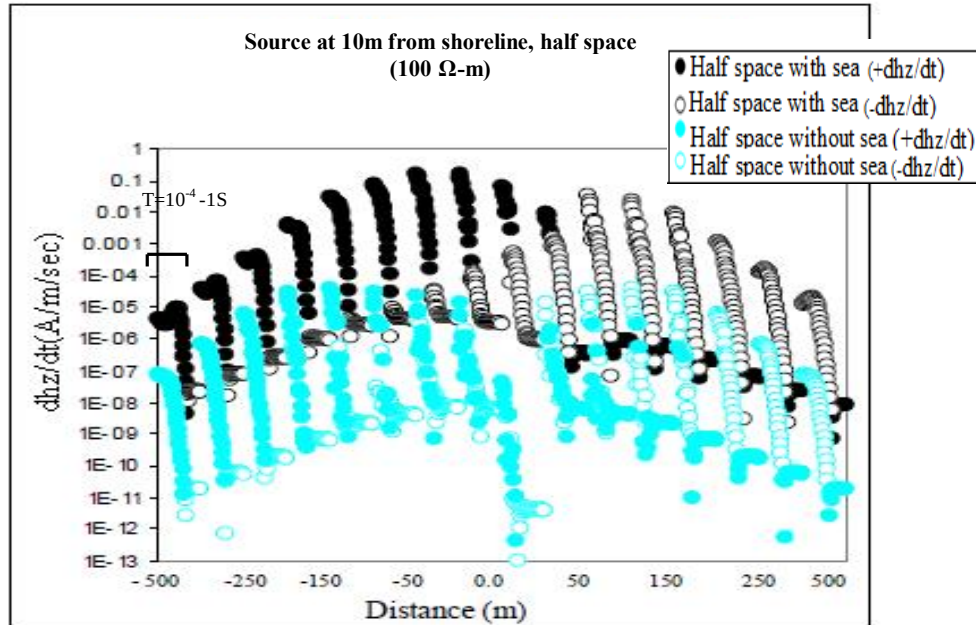
Figure 3.7. A sketch of the grid cells used for the 3-D EM modeling in this study.

3.4.2. Comparison of Sea effect and the source position from shoreline

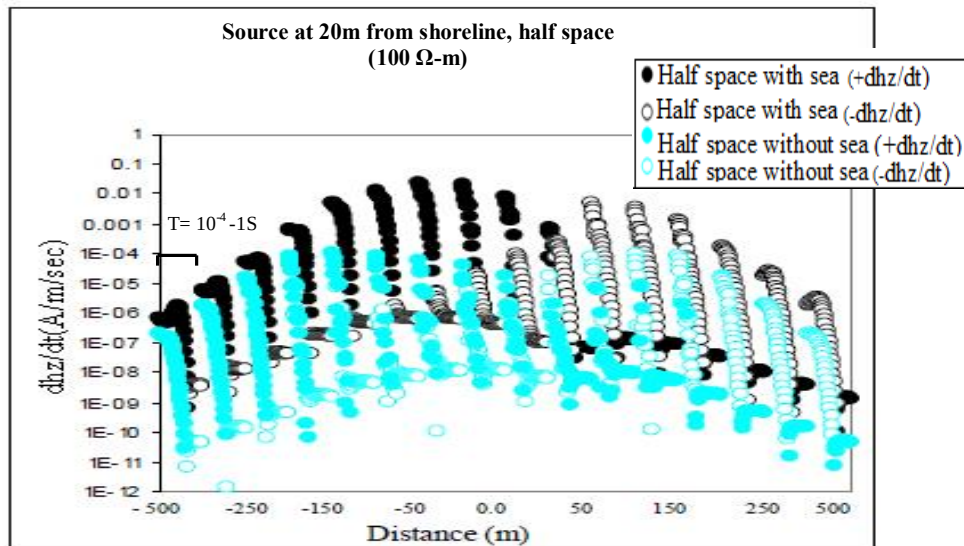
Figure 3.8 (A, B, and C) shows a comparison of the time derivative of h_z between half-space (100 q -m) with/without sea (0.3 q -m) in the three cases of source position

from the shoreline (10, 20, and 300 m), respectively (Figure 3.6). These figures indicate the initial response curve plotted at each site. (D) Represents the percentage difference in the response of dhz/dt for the three dipole source locations from the coastline (10, 20, and 300 m) cases shown in (A), (B), and (C). As shown in the figure, if the dipole source position is located 10 m from the shoreline, the effect of the sea on EM field induction is greater than if the dipole position is located 20 or 300 m from the shoreline.

(A)

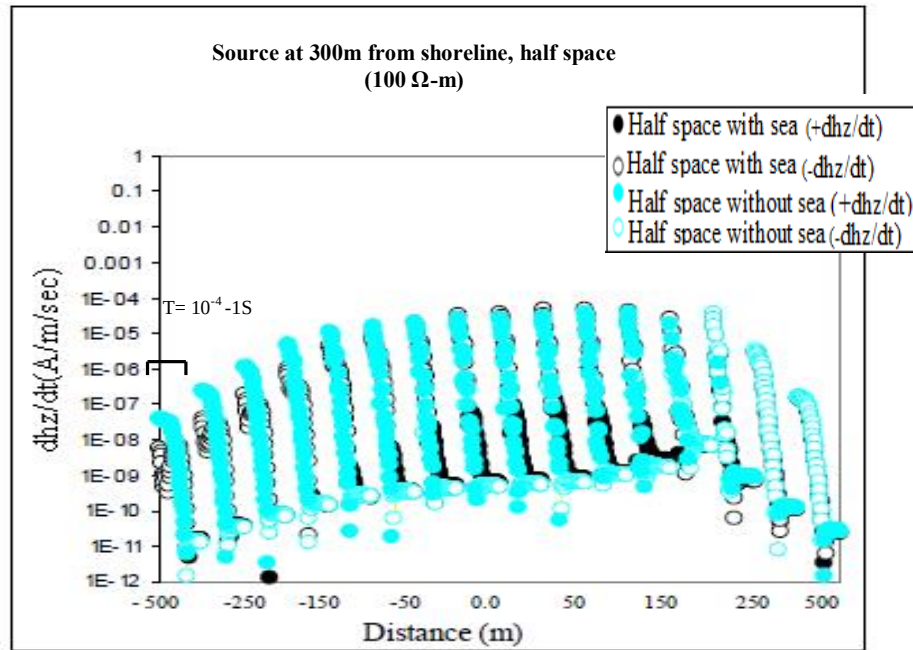


(B)



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(C)



(D)

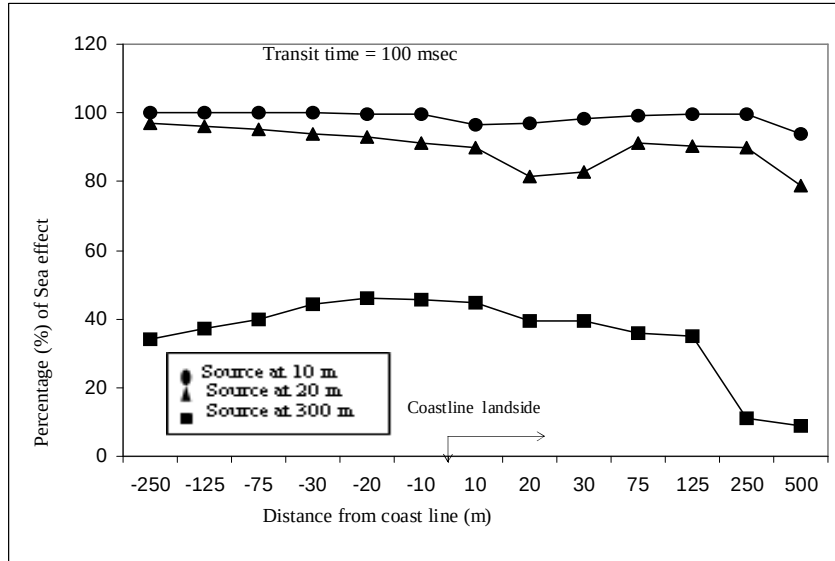
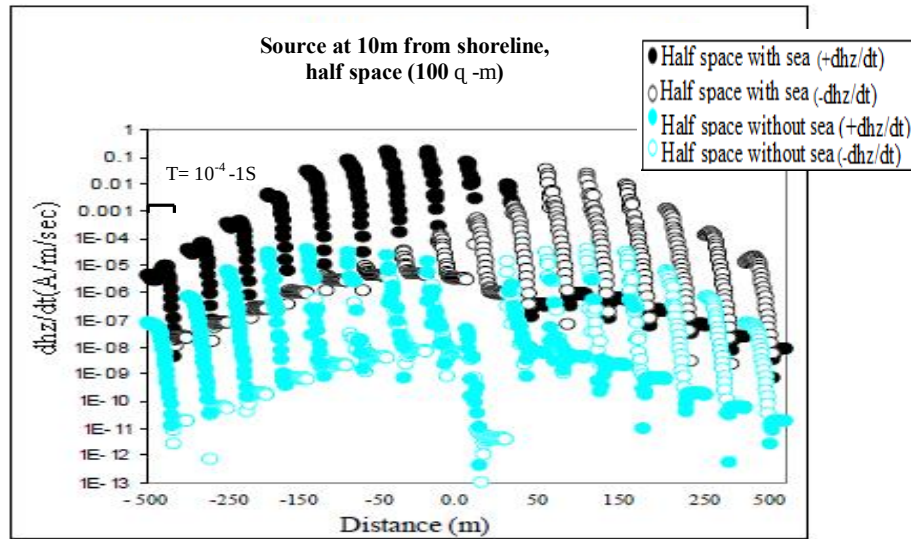


Figure.3.8. (A), (B), and (C) are comparisons of the time derivatives of dhz/dt between half-space with sea (black)/without sea (blue) for three source positions from the shoreline (10, 20, and 300 m), respectively (Figure 3.6). (D) Percentage differences in the responses of dhz/dt for the three cases shown in (A), (B), and (C).

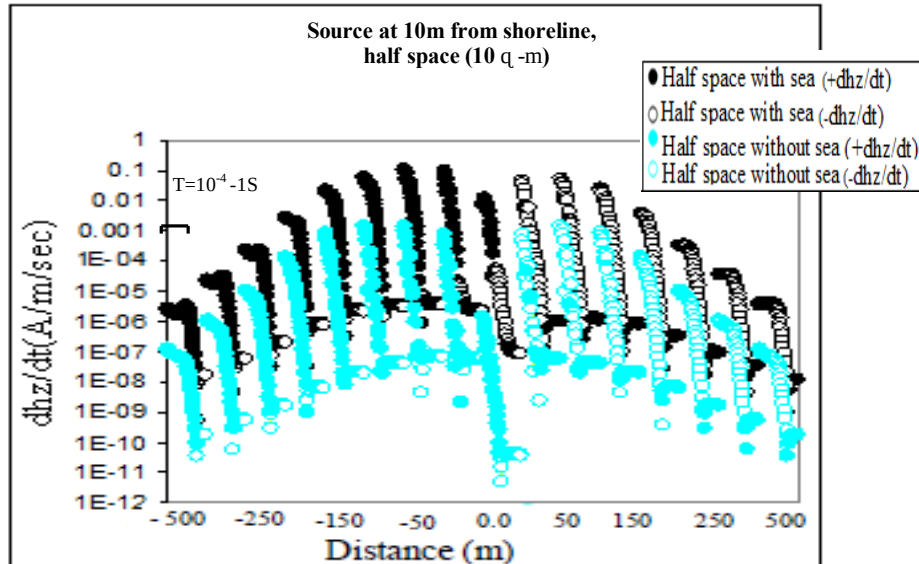
3.4.4. Comparison of Sea Effect and Host Rock Resistivity

To study the relationship between the sea effect and host rock conductivity, I repeated the computation of the sea-land boundary model (Figure 3.6) with uniform half-space Earth medium resistivities of 10 and 1 q-m, instead of 100 q-m. Figure 3.9 (A, B, and C) shows the comparison of time derivative of h_z between half-space with/without sea in the three cases of half-space resistivities (100, 10, and 1 q-m) respectively. The source is located at 10 m from the shoreline.

(A)



(B)



Continued in the next page

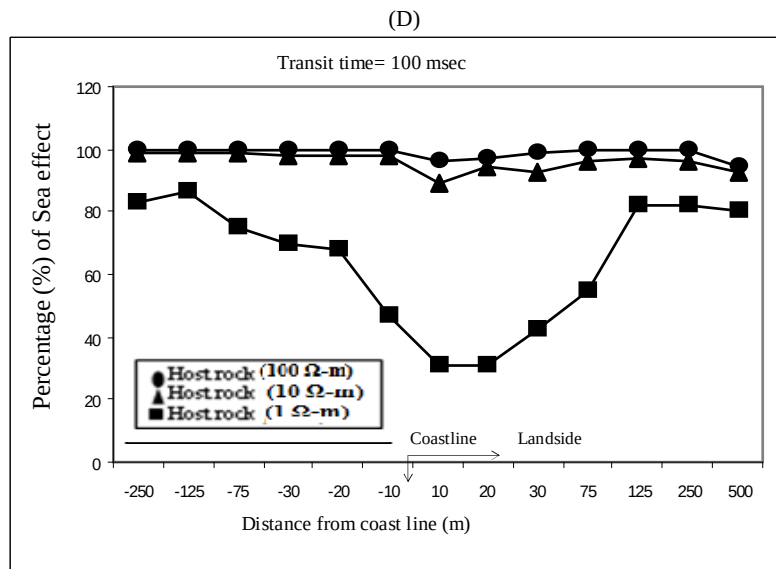
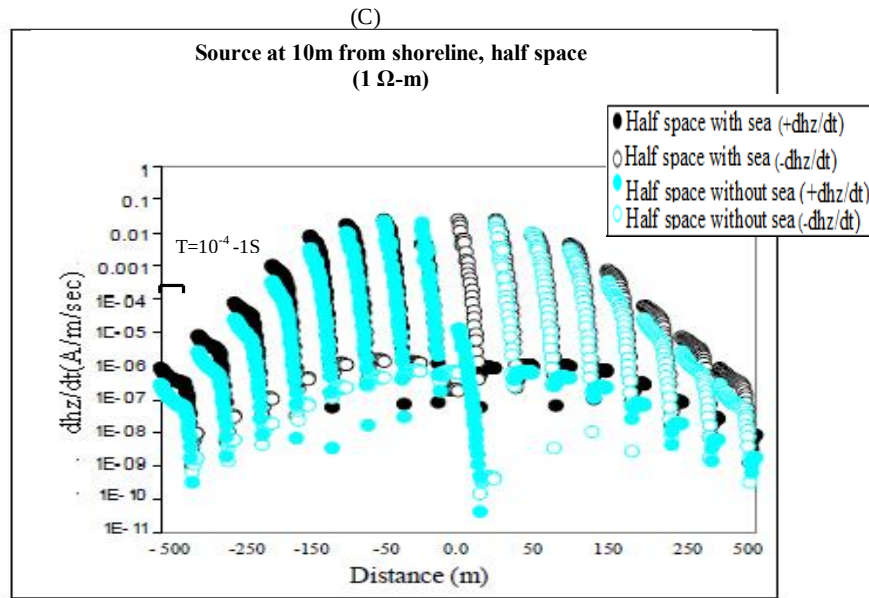


Figure.3.9. (A), (B), and (C) are comparisons of the time derivatives of h_z between half-space with sea (black)/without sea (blue) in three cases of host rock (100, 10, and 1 Ω -m, respectively). (D) Percentage differences in the dhz/dt response for the three cases shown in (A, B, and C). The source position is 10 m from the shoreline.

(D) An example of the sea effect represented by the percentage difference in the response of dhz/dt for the three cases showed in (A), (B), and (C). The effect of the sea on EM field induction is greater for a host rock resistivity of 100 q -m than for host rock conductivities of 10 and 1 q -m.

This indicates that the effect of the sea on EM induction is inversely proportional to the host rock conductivity.

3.4.5. Topography Model

Topography in our model was represented as an anomaly in the air layer in which resistivity was assumed at 10^8 q -m. I selected a 3-D topographic model consisting of a topographic feature (100 q -m) placed on top of a uniform half-space Earth medium (100 q -m) as shown in figure 3.10.

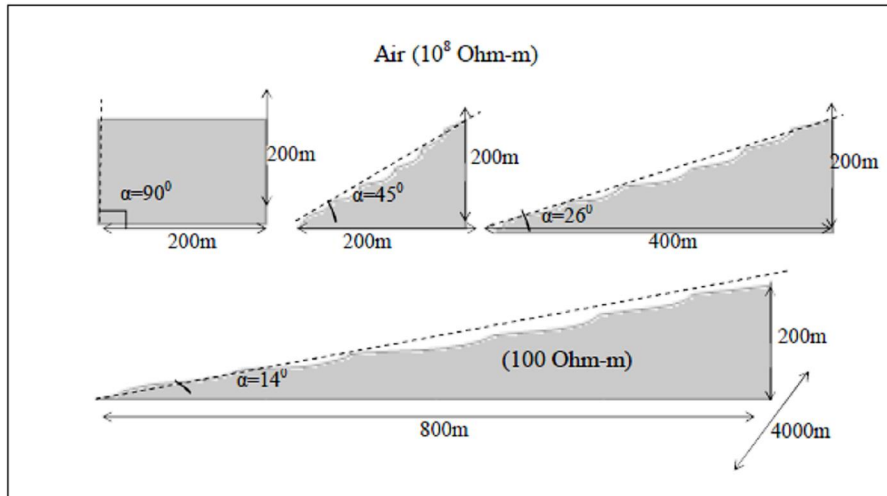


Figure 3.10. The 3-D topography models. Topography (100 q -m) with different slope angles (α) placed on top of a uniform half-space Earth medium (100 q -m).

The resistivity contrast was 10^6 times between the air and the topography. In the topographic area, I used $x: 50 \times y: 50 \times z: 25$ -m cells. Outside the topographic area, irregular cells were used. The total number of nodes was $52 \times 38 \times 32 = 63,232$ cells. The computations were performed for four topographic slope angles (α) = 90° [topography width is 200 m ($x = 0$ to 200 m), and its height is 200 m], (α) = 45° [topography width is 200 m ($x = 0$ to 200 m), and its height is 200 m], (α) = 26° [topography width is 400 m ($x = 0$ to 400 m), and its height is 200 m] and (α) = 14°

[topography width is 800 m ($x = 0$ to 800 m), and its height is 200 m]. In the four cases, the topography width in the y direction is 4000 m ($y = -2000$ to 2000 m), as shown in figure 3.10. A horizontal electrical dipole source was directed along the y -axis situated at $x = -1500$.

Figure 3.11 shows a comparison of the dhz/dt response for the topographic slope angles of 14° and 45° with the response of the uniform half-space Earth medium (Figure 3.10) at different ground levels (H). At a low ground level of 50 m, topography has a 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° .

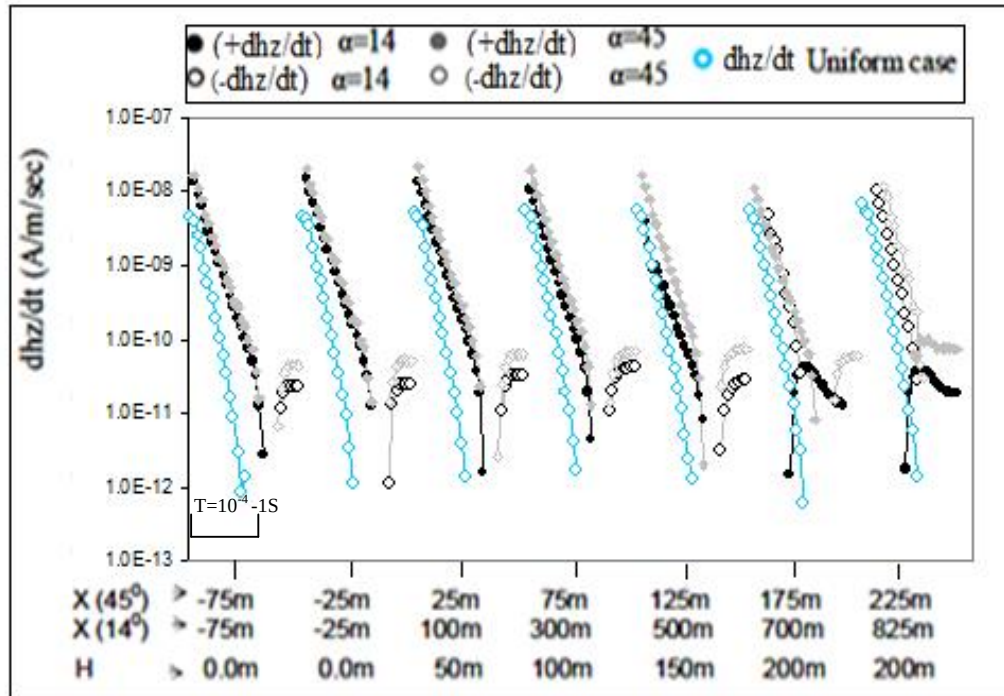


Figure 3.11. Comparison of the dhz/dt responses among topography with slope angles (α) of 14° (black), 45° (gray), and a uniform half-space Earth medium (blue) at different ground levels (H). The transient time $T = 10^{-4}$ to 10^0 s.

Figure 3.12 shows the effect of topography represented by the percentage difference in the response of dhz/dt between the uniform half-space with or without topography for topographic slope angles 90° , 45° , 26° , and 14° (Figure 3.10) at different ground levels (H). The effect of topography is most significant for a steep slope angle (90°) than for gentler

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.

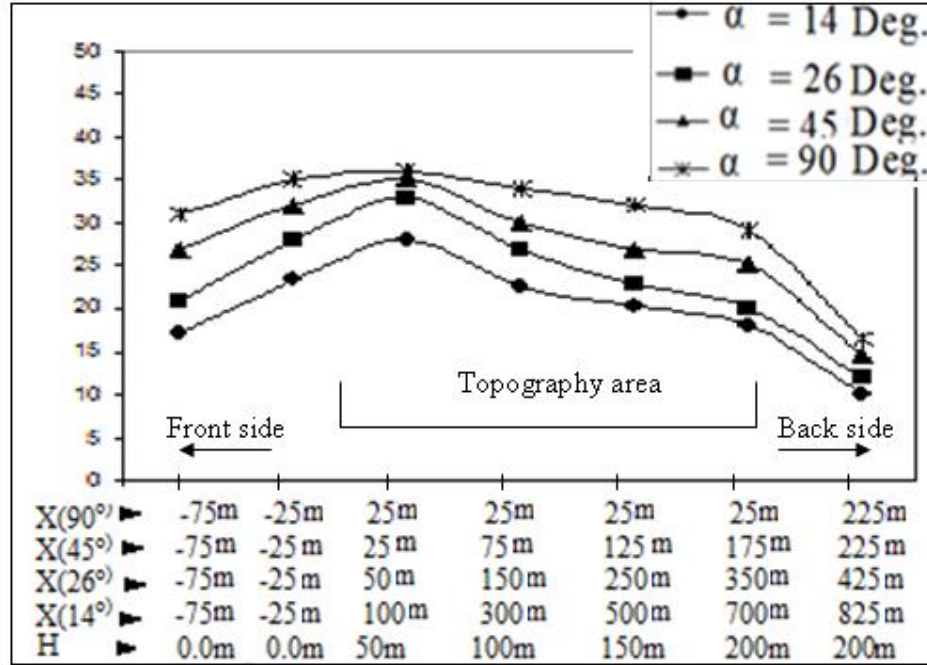


Figure 3.12. The percentage differences in the dhz/dt response between host rock with or without topography for four topographic slope angles ($\alpha = 90, 45, 26, \text{ and } 14^\circ$) at different ground levels (H).

3.5. Results Summary

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

1. Our 3-D EM modeling computing scheme, which is based on the SFD method, has been verified by comparing the results of a quarter-space and trapezoidal hill models with the results of the 2.5-D FEM developed by Mitsuhashi (2000), and the 3-D SLDM method developed by Druskin and Knizhnerman (1994). Although minor differences are present, the main features of the three results are similar. This confirms the accuracy and credibility of our computing method.
2. The sea effect on EM field induction at sea-land boundaries using GREATER surveys depends on the position of the ground electrical dipole source relative to the shoreline. For example, the coast effect when the source is located 10 or 20 m landward from the shoreline is greater than when the source is 300 m from the shoreline. The sea effect also depends on the host-rock resistivity. For example, if the host-rock

resistivity is 100 q -m, the effect of the sea on EM field induction is higher than for 10 or 1 q -m.

3. The most significant effect of topography on EM field induction occurs at low ground levels and decreases gradually with increasing ground level. The topographic effect of steep slope angles (e.g., 90 and 45°) is greater than for gentler slopes (e.g., 26 and 14°). The percentages of the topography effect are ca. 52, 45, 33, and 29% in the cases of 90, 45, 26, and 14° of topographic slope angle, respectively.

3.6. Conclusions

The sea effect on GREATEM survey data is inversely proportional to both the distance of the dipole source from the shoreline and 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 greater 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 relies heavily on an obvious presumed structure.

Chapter 4

Three-dimensional Resistivity Modeling of a Coastal Area Using GREATEM Survey Data from Kujukuri Beach, Chiba, Central Japan

4.1. Introduction

Coastal areas are vulnerable to natural disasters such as earthquakes, tsunamis, and hurricanes (e.g., Mallin and Corbett, 2006; Wang *et al.*, 2006; Hornbach *et al.*, 2010). Mapping the subsurface physical properties of coastal areas is useful for mitigating natural disasters and sustaining comfortable environments. An important property is electrical conductivity, which is increased by the presence of conductive minerals. Considerable geological heterogeneity in conductivity exists both vertically and laterally along the coast. Inverted electrical conductivity models provide remarkable insight into complex coastal stratigraphy and enable a better understanding of groundwater-surface water exchange processes (Hallier *et al.*, 2008). This information, together with an appreciation of the significant rising of seawater levels due to tsunamis and hurricanes, is critical for the sound management of water resources and coastal area development strategies.

The use of airborne electromagnetic (AEM) techniques for groundwater monitoring and modeling has increased steadily in the past decade (e.g., Steuer *et al.*, 2009) owing to advances in AEM systems and processing and in inversion methodologies. However, few studies have applied AEM in areas such as lagoons, wetlands, rivers, or bays, and previous studies have mainly focused on bathymetric data (e.g., Vrbancich and Fullagar, 2007). Viezzoli *et al.* (2010) demonstrated the suitability of the SkyTEM helicopter-borne transient electromagnetic (EM) system (Sørensen and Auken, 2004) for investigating surface water and groundwater exchange in transitional coastal environments. They investigated an area at the southern margin of the Venice Lagoon, Italy, where very shallow surface water (less than 1 m), tidal marshes, large rivers, and

several reclamation channels, combined with a complex morphological, geological, and hydrological setting, had precluded in-depth traditional investigation. In this coastal area, AEM data were used to probe the resistivity structure to a depth of ~200 m.

New applications of AEM survey techniques have been introduced in engineering and environmental fields, particularly for studies involving active volcanoes (Mogi *et al.*, 2009). Time-domain methods offer advantages over frequency-domain methods, such as an increased depth of investigation and detail, as well as more accurate mapping of freshwater/saltwater boundaries (Steuer *et al.*, 2009).

Ships designed for surveying at sea are generally difficult to use in shallow coastal areas, whereas AEM surveys can span both onshore and offshore areas. Walker *et al.* (2004) presented a synthesis of salinity management studies in five South Australian catchments. The field of airborne geophysics was tailored to answer specific salinity problems and was then integrated with hydrologic/hydrogeological data and modeling to contribute to the design and implementation of land-use management strategies. Wilkinson *et al.* (2005) integrated airborne geophysical data with more traditional environmental approaches to map potential salt stores, recharge, and discharge sites in the Goondoola basin, southwest Queensland, Australia, and subsequently developed land-management recommendations. In that study, the integration of surficial and subsurface electromagnetic datasets allowed the researchers to extrapolate and map surface salinity outbreaks and identify similar landscape settings at risk of developing salinity from groundwater rise.

One significant problem limiting the use of AEM surveys in lagoons, wetlands, rivers, and bay areas is the presence of the conductive saline surface water that decreases the penetration depth of the AEM signal. However, the moment of the transmitter loop has been increased in recent AEM systems. In other words, their penetration power has increased, as has the quality of the data obtained. This, together with advances in AEM modeling and inversion procedures, can produce quantitative results useful for groundwater modeling in coastal areas.

Real subsurface structures are three-dimensional (3-D) by nature. Although one-dimensional (1-D) models based on horizontal layers are adequate in many exploration situations, there are also numerous cases, such as for over thrusts, salt domes, and anticlines, where 3-D modeling is required (Hoerdt *et al.*, 1992). Here I present a 3-D

resistivity modeling study to examine the capability of the GREATEM system (Mogi *et al.*, 1998) to provide accurate data on coastal areas, especially in the presence of shallow seawater (Ito *et al.*, 2011). The GREATEM method allows for the application of a large-moment source and use of a long transmitter–receiver distance, increasing the survey depth to ~800 m in inland areas (Mogi *et al.*, 2009), compared to the ~300 m depths possible using conventional AEM techniques.

4.2. Survey Area

Kujukuri Beach is a sandy beach located on the northeast coast of the Boso Peninsula in Chiba Prefecture, central Japan. It is the second-longest beach in Japan and is located within 60 km of Tokyo (Figure 4.1). The shore-face is barred, with gradients of 1/150 at a water depth of 0 to 5 m and 1/200 at 5 to 15 m depth (Tamura *et al.*, 2008). The landward margin of the Kujukuri coastal plain is defined by a plateau and hills, rising to ~30 m above sea level. Seven rivers run through the strand plain, but their contribution to the offshore sediment supply off the coast has been relatively small. The landforms on the Kujukuri plain include beach ridges, sandy dunes, inter-ridge swales, and floodplain (Moriwaki, 1979). Rows of beach ridges run parallel or sub-parallel to the shoreline. The subsurface stratigraphy across the central part of the Kujukuri coastal plain has been revealed from drill core studies conducted by Masuda *et al.* (2001) and Tamura *et al.* (2003). Holocene marine sediments approximately 20 m thick overlie the eroded Plio-Pleistocene basement rocks and earlier Holocene incised-valley deposits. The marine sediments consist mostly of very fine to medium sand with mollusc shells and compose the basal, lower and upper shore-face, and backshore facies, in ascending order. The base of the marine succession marks the erosional ravinement surface formed in response to the rapid sea-level rise that occurred during the early and middle Holocene.

The survey group selected this area for our study because of its shallow seawater depth and the availability of resistivity data for comparison. Previous studies in the Kujukuri area were conducted by Mitsuhashi *et al.* (2006), Uehara *et al.* (2007), and Hayashi *et al.* (2009). Mitsuhashi *et al.* (2006) applied three types of ground electromagnetic survey techniques: audio-frequency magnetotelluric, transient electromagnetic (TEM), and small loop–loop EM measurements. These studies revealed resistive features to a depth

of ~500 m on the landward side of the coast and the presence of deep fossil saline water beneath. Uehara *et al.* (2007) applied electrical resistivity measurements along a land/seafloor crossing line and revealed a resistivity structure to a depth of ~40 m on the seaward side of the coast. Hayashi *et al.* (2009) reported wellbore logging data from 30 m to 1660 m depths adjacent to our study site. Their data indicated that a low-resistivity zone of ~2 Ω -m exists from 30 m to at least 1000 m in depth.

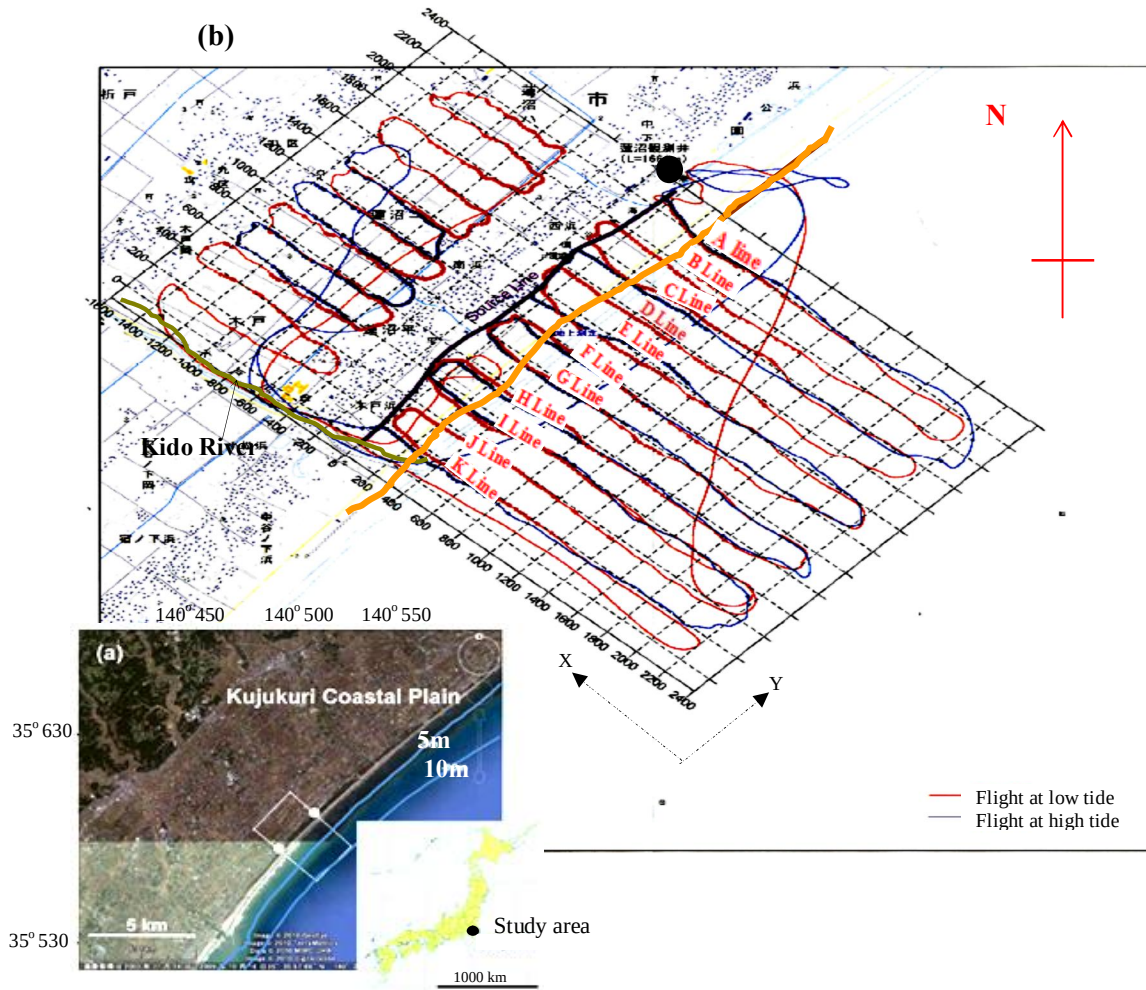


Figure 4.1. Location of survey area in the Kujukuri coastal plain with 5 and 10 m bathymetric contours. White dots in (a) denote the places where current dipole electrodes were placed (modified from Ito *et al.* 2011). (b) The study area on the Kujukuri coastal plain and flight lines. The thick brown line indicates the shoreline and the thick black line indicates the transmitter cable, which was placed ~300 m inland ($x = 0.0$) and parallel to the shoreline ($x = 300$). Meaningful data were obtained on flight lines with thicker color. The thicker dots on the flight lines indicate places where clear transient responses used for modeling were obtained.

4.3. Data Acquisition

In the current study, a helicopter-based airborne survey was conducted along 11 flight lines (line A-line K) spaced 200 m apart (Figure 4.1). Because of flight regulations in Japan, residential areas were avoided.

The signal source was a time-varying current of ~ 25 A transmitted underground by a grounded electrical-dipole source 2.4 km long that was set ~ 300 m inland parallel with the shoreline (Figure 4.1). Three components of the secondary magnetic field related to the underground resistivity were recorded in the atmosphere by a sensor mounted in a bird towed by the helicopter.

The magnetic field responses were recorded with the current both $\cos\omega t$ and $\sin\omega t$. Only current $\cos\omega t$ time data were used because they were of better quality than those for when the current was $\sin\omega t$. The waveforms were digitized through a 16-bit AD converter at a rate of 80 microseconds (ϵs), and 20,000 sets of data were recorded during one cycle of 1.6 seconds (sec). For flight safety, the bird was flown at ~ 100 m height, and the measured data were subsequently processed to reduce noise. The sensor altitude was monitored using a Global Positioning System (GPS) device attached to the bird, and the sensor height above the ground (terrain clearance) was obtained by taking the difference between the sensor altitude and the topographic elevation interpolated from a 50 m grid digital elevation map provided by the Geospatial Information Authority of Japan.

4.4. Data Processing

Options for time-domain data stacking on a moving aircraft are limited. Monitoring and filtering motion-induced noise in the data, removing natural magnetic field variation, and limiting cultural noise are important signal conditioning processes that must be performed. Data processing flow chart used in this study are the same as those described in figure 2.4 in chapter 2. Finally, after data processing the maximum error of the data was within 5%.

4.5. One-dimensional Inversion Results

One-dimensional (1-D) results are performed by Ito *et al.*, 2011. Here I describe the results after them. The waveforms, after noise reduction and stacking, were clear on the

land-side (200 m from the source), but become gradually noisier offshore, such that they were undetectable at 800 m offshore (1100 m from the source) (Ito *et al.*, 2011). Figure 4.2 shows the northwest-southeast cross-section of the 1-D resistivity structure along the flight line K ($y = 200$ m). A low resistivity of ~ 1 Ω -m was found in most areas beneath both land and sea. Higher resistivity structures (3-25 Ω -m), referred to here as a high-resistivity landmass, were found at depths of as much as 40 m between the shoreline ($x = 300$ m) and ~ 300 m inland ($x = 0.0$ -260 m). Another highly resistive structure (~ 15 Ω -m) also existed at both depths of ~ 100 m and 300 m beneath the beach between 350 m and 500 m offshore ($x = 650$ -800 m) (after Ito *et al.*, 2011). The high-resistivity land mass resides in the K-Line, which lies almost along a river (Figure 4.1), therefore this landmass corresponds to either thick sand deposits, or less saline groundwater mass, or both (Ito *et al.*, 2011).

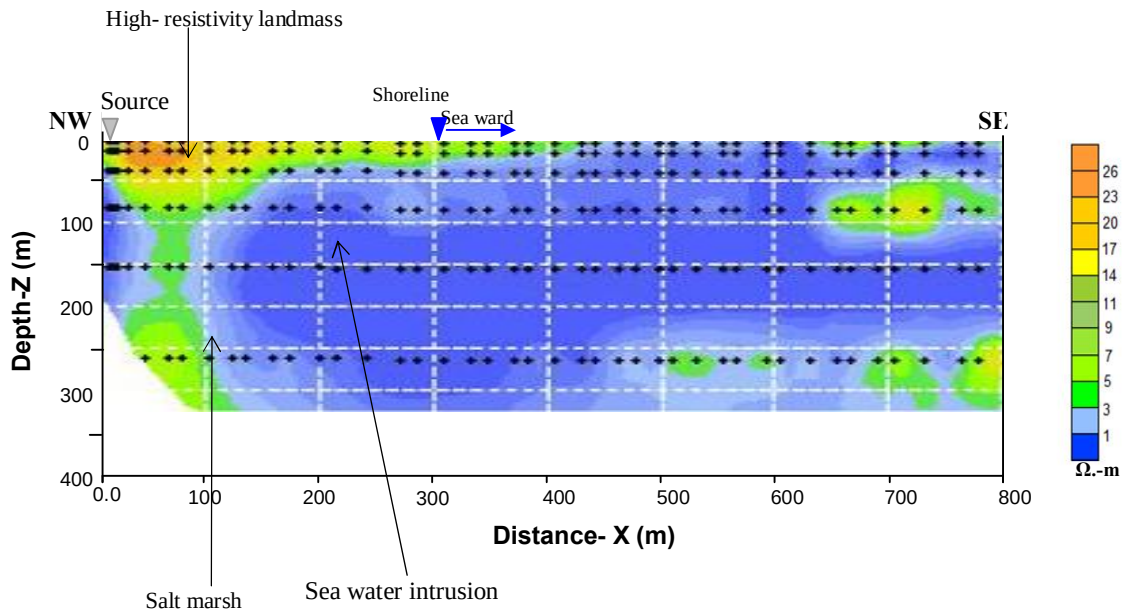


Figure 4.2. Northwest-southeast 1-D resistivity section along the flight line K (easting 200 m). (After Ito *et al.*, [2011].)

4.6. Three-dimensional Modeling of GRETEM Field Data at Kujukuri Beach

Large resistivity contrasts between land and sea are a serious issue in surveys of coastal areas. A horizontally layered resistivity structure might be distorted in this

situation. Although, the 1-D inversion results of the current study were acceptable in comparison with previous results by other geophysical methods in the same study area, they could not reflect the real size and contrast of resistivity features. To overcome this problem, I tried to construct a 3-D resistivity model that considered large changes in lateral resistivity. I used the modified SFD method Fomenko and Mogi (2002) and Mogi *et al.* (2011) which is described in the chapter 2. To generate the 3-D resistivity structure model of our study area. A 3-D model of (x: 16.5 x y: 14.2 x z: 9.2) km³ was designed and divided into (x: 50 x y: 50 x z: 31) = 77500 cells using grid coordinates similar to the survey area. In the vertical direction, the size of each grid varied from 5 m at the surface to 6400 m at the top and bottom of the model. The horizontal size was ~200 m in the modeling area, and large-sized (800-6400 m) grids were added at the circumference of the modeling area to avoid an edge effect. The 3-D resistivity model was based on an initial model of 1-D resistivity structures inverted from the GREATEM field survey data. Convolution was applied in the frequency domain to account for the frequency response characteristics of the field survey instrument. The results were then compared with the processed survey data of transient response. The field data were stacked within each cell and the transient response curves of the field data were fitted to the transient response curve of the 3-D-computed data obtained at the center of the cell. I used a trial and error method, in that the resistivity values of initial model were repeatedly changed to obtain a good fit between the 3-D synthetic response and field data. In the case of the field survey, 10,000 samples of data digitized at a rate of 80 εs were obtained during half cycle of 0.8 sec. However, in the case of numerical modeling, 40 transient responses were computed at 40 time channels and 10 time-equal spaces of a log scale in one decade, in the range of 100 εs to 1 sec (4 decades). I therefore used only those data of the same time channels (30 samples) and computed the root mean-square error (misfit) between normalized intensity by maximum amplitude (dhz/dt) of both field data and modeling responses for different blocks of the 3-D model that corresponded to the survey area. The percent root mean-square misfit was defined as $[\| \times (\text{dobs} - \text{dcal}) \|^2 / N]^{1/2} \times 10^2$.

For all of the 3-D modeling data, the best fit with field data was found with root mean-square error (RMSE) 2 to 5%. Examples for different fitting RMSEs of the model response with field data of the F flight line (RMSE=2%), K flight line (RMSE=3%),

and C flight line (RMSE=5%) are shown in figure 4.3 (A, B, and C) respectively. Kinks and turns appear on the transit response curves owing to the 3-D effects from horizontal resistivity change. The misfit errors of the 1-D inversion of data on the same flight lines were about 3.8%, 3.7%, and 5.6%, respectively. In comparison with the 3-D data misfit, data fitting was improved in the case of the 3-D inversion rather than the 1-D inversion. The 3-D modeled responses that best fit the field data were used to generate the 3-D resistivity model of the study area (Figure 4.4).

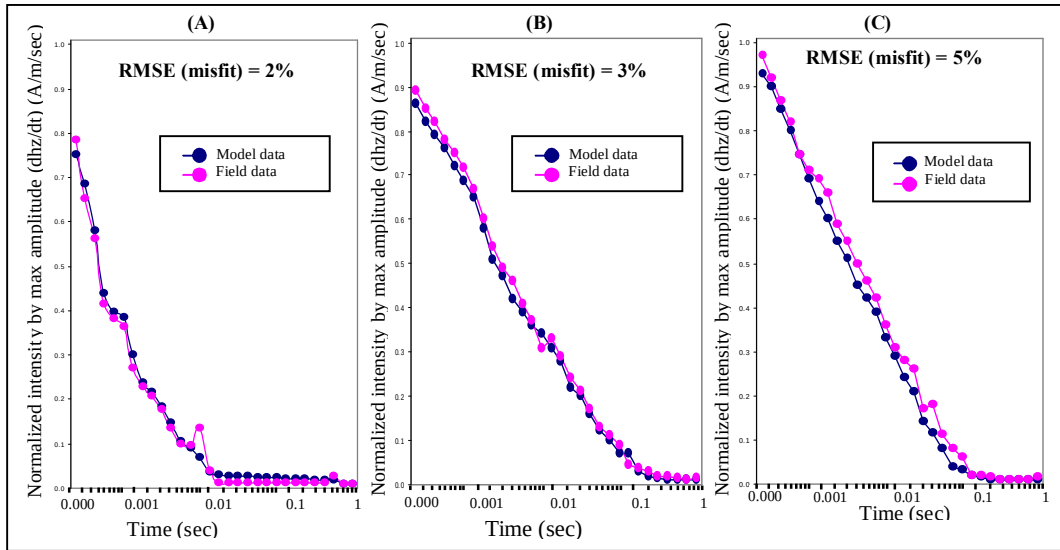


Figure 4.3. An example for fitting the transient response curves between observed field data and 3-D numerical model data at (A) flight line F (RMSE = 2%), (B) flight line K (RMSE = 3%), and (C) flight line C (RMSE = 5%).

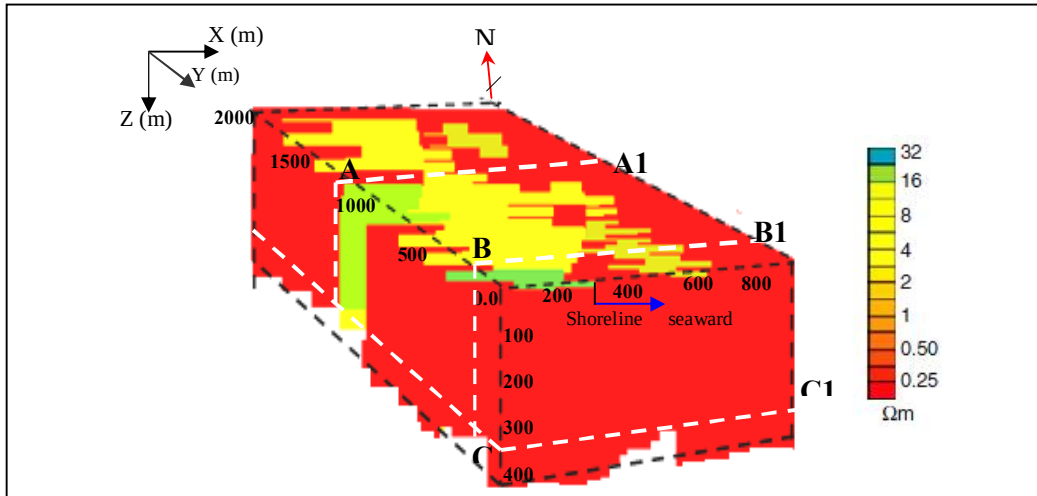


Figure 4.4. Schematic of the 3-D resistivity structure model of the GREATER data for Kujukuri beach. The red arrow indicates the shoreline which is ~400 m from the source. A-A1 is a resistivity profile of the 3-D model corresponding to the F flight line ($y = 1200$ m), B-B1 is a resistivity profile of the 3-D model corresponding to the K flight line ($y = 200$ m), and C-C1 is a resistivity profile of the 3-D model at $z = 350$ m.

4.7. Three-dimensional Synthetic Modeling Results

Figure 4.5 shows the northwest-southeast cross-section of the 3-D-resistivity model along the profile A-A1 (Figure 4.4), which corresponds to the F flight line ($y = 1200$ m).

As shown in this figure, low resistivity (< 2 q-m) is dominant beneath both land and sea. A slightly higher resistivity structure (2-5 q-m) exists between 100 m and ~300 m onshore ($x = 0.0$ -200 m) and extends to depths of as much as 400 m. This structure can be interpreted as seawater intrusion. Another highly resistive structure (8-24 q-m) exists at 200 m to ~300 m onshore ($x = 0.0$ -100 m) and extends to 25 m depth. This structure may correspond to a less saline groundwater mass influenced by a nearby river (Figure 4.1).

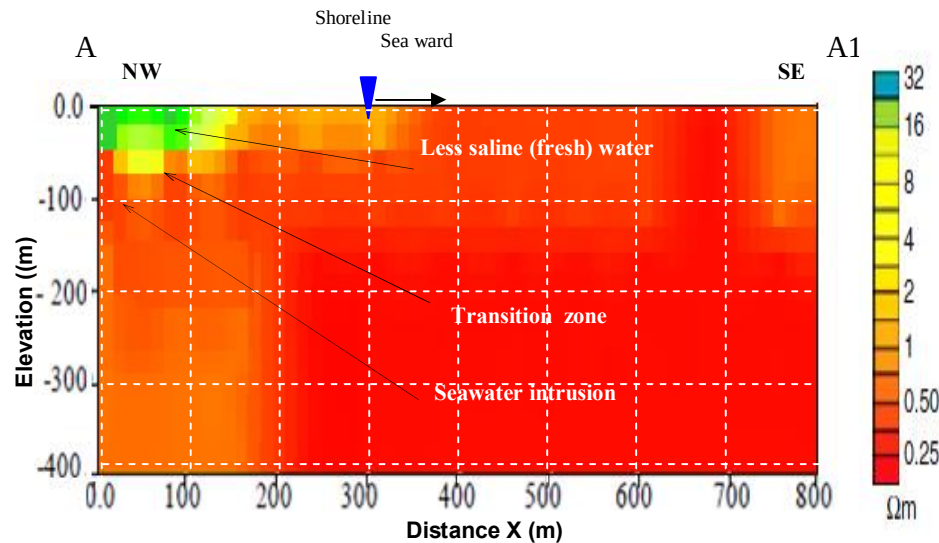


Figure 4.5. Northwest-southeast cross-section of the 3-D model along the profile A-A1, as shown in figure 4.4.

Figure 4.6 shows the northwest-southeast cross-section of the 3-D model along profile B-B1 (Figure 4.4), corresponding to the K flight line ($y = 200$ m). It reveals that low resistivity (< 2 q-m) is dominant beneath both land and sea. A landmass with high resistivity (5-24 q-m) exists to a depth of ~100 m at 80 m seaward from the shoreline to ~300 m inland ($x = 0.0$ -380 m). A resistive structure (3-8 q-m) also exists to a depth of ~350 m beneath the beach between 350 and 500 m offshore ($x = 650$ -800 m). This structure can be interpreted as a permeable sedimentary layer in shallow water because it has a similar resistivity value as the sedimentary structures found inland side (Uehara *et al.* 2007).

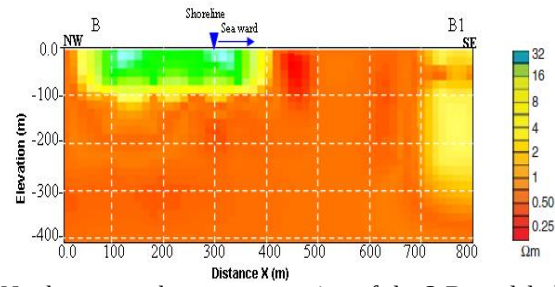


Figure 4.6. Northwest-southeast cross-section of the 3-D model along the profile B-B1, as shown in figure 4.4.

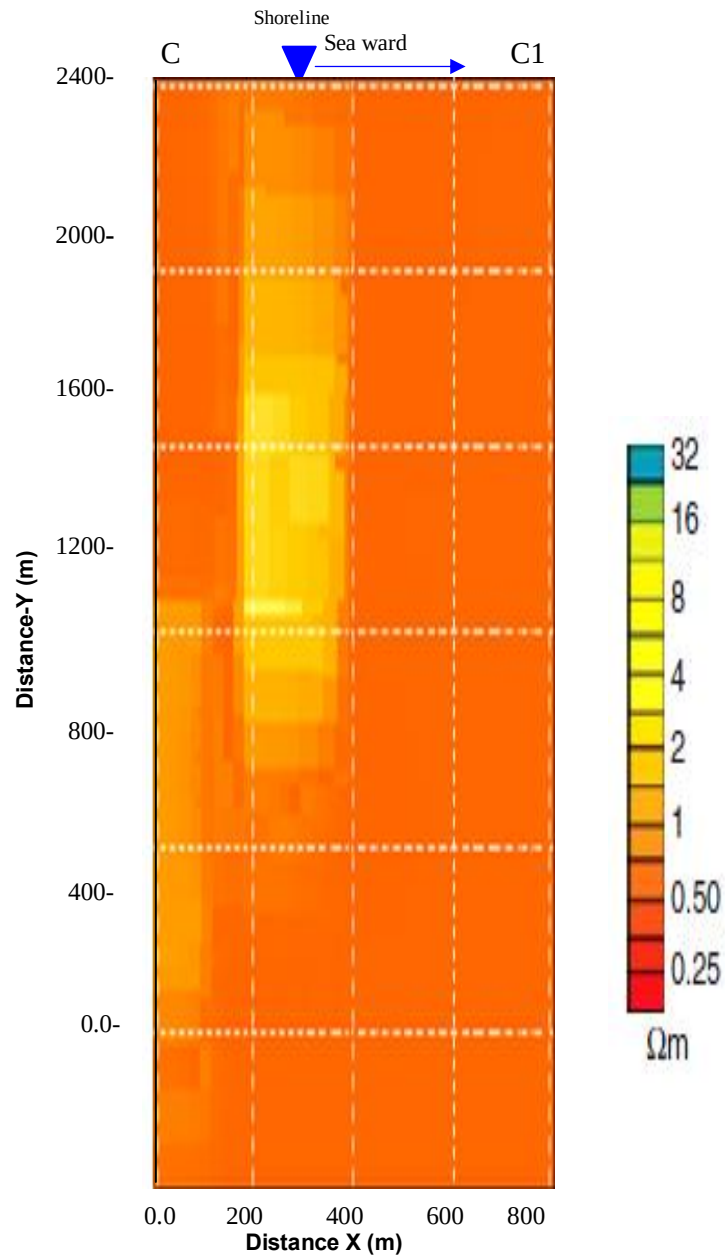


Figure 4.7. Northwest-southeast cross-section of the 3-D resistivity model along the profile C-C1 at a depth of 350 m as shown in figure 4.4.

Figure 4.7 shows a depth slice of the 3-D resistivity model along profile C-C1 (Figure 4.4) at $z = 350$ m. A moderately resistive structure (3-5 q-m) is shown between ~ 300 m onshore and ~ 300 m offshore ($x = 0-600$ m ; $y = 900-2100$ m).

The robustness of the resistivity models were tested by computing the 3-D model again, this time with the removal of some resistivity structures, for example removing a 250 m thickness from the resistivity structure in figure 4.7. Removing this thickness from the resistivity structure increased the global misfit error between the 3-D model response and field data more than the percentage of measuring data error, indicating the accuracy of the model in this figure.

4.8. Comparison of 1-D and 3-D Resistivity Models

Figure 4.8 shows the northwest-southeast resistivity structure profiles along the K flight line ($Y = 200$ m) comparing the 1-D (after Ito *et al.*, 2011) and 3-D inversion models. In both the 1-D and 3-D models, structure R1 had a resistivity value of 2-25 q-m and existed to a depth of 100 m beneath the beach between 150 and 300 m from the shoreline inland ($x = 0.0-150$ m). In case of the 1-D model, structure R2 had a resistivity range of 2-11 q-m and existed to a depth of ~ 50 m between ~ 120 m seaward from the shoreline and ~ 150 m inland ($x = 150-420$ m). However, in the 3-D model, this structure had resistivity values of 2-25 q-m and existed to a depth of ~ 100 m between 80 m seaward from the shoreline and 150 m inland ($x = 150-380$ m). In addition, structure R3 in the 1-D model had resistivity values of 2-11 q-m and existed at a depth range of 100-320 m beneath the beach between 180 and 250 m from the shoreline inland ($x = 50-120$ m), but in the 3-D model this structure had resistivity values of 2-5 q-m and existed at depths of 100-180 m beneath the beach between 120 and 280 m from the shoreline inland ($x = 20-180$ m). Also, in the 1-D model, structure R4 had a resistivity values of 2-15 q-m and existed at 50-120 m depth beneath the beach between ~ 350 and 500 m offshore ($x = 650-800$ m); however, in the 3-D model, this structure had a resistivity range of 2-11 q-m and existed at 50-120 m depth beneath the beach between ~ 350 and 500 m offshore ($x = 650-800$ m). Furthermore, in both the 1-D and 3-D models, structure R5 was found at 240-320 m depth beneath the beach between ~ 350 and 500 m offshore ($x = 150-420$ m); it had a resistivity range of 2-15 q-m in the 1-D model but 2-8 q-m in the 3-D model.

Structure R6 showed resistivity of 2-11 q-m and existed at depths of 120-250 m beneath the beach between ~350 and 500 m offshore ($x = 650-800$ m); this structure was recovered only by the 3-D model results.

Overall, these figures show similar resistivity distributions, but with different resistivity boundaries and values.

The main difference between the 1-D and 3-D inversion results is that the 1-D computation assumed a layer structure and did not consider lateral resistivity change. Since the computation processes of 1-D inversion assume horizontal layers that extend to infinity, the conductor thickness and its contrast are too small to recover the observed data at point by point. However, a 3-D inversion model reflects a real size, tends to have larger conductor size, and its contrast better explains the observed values.

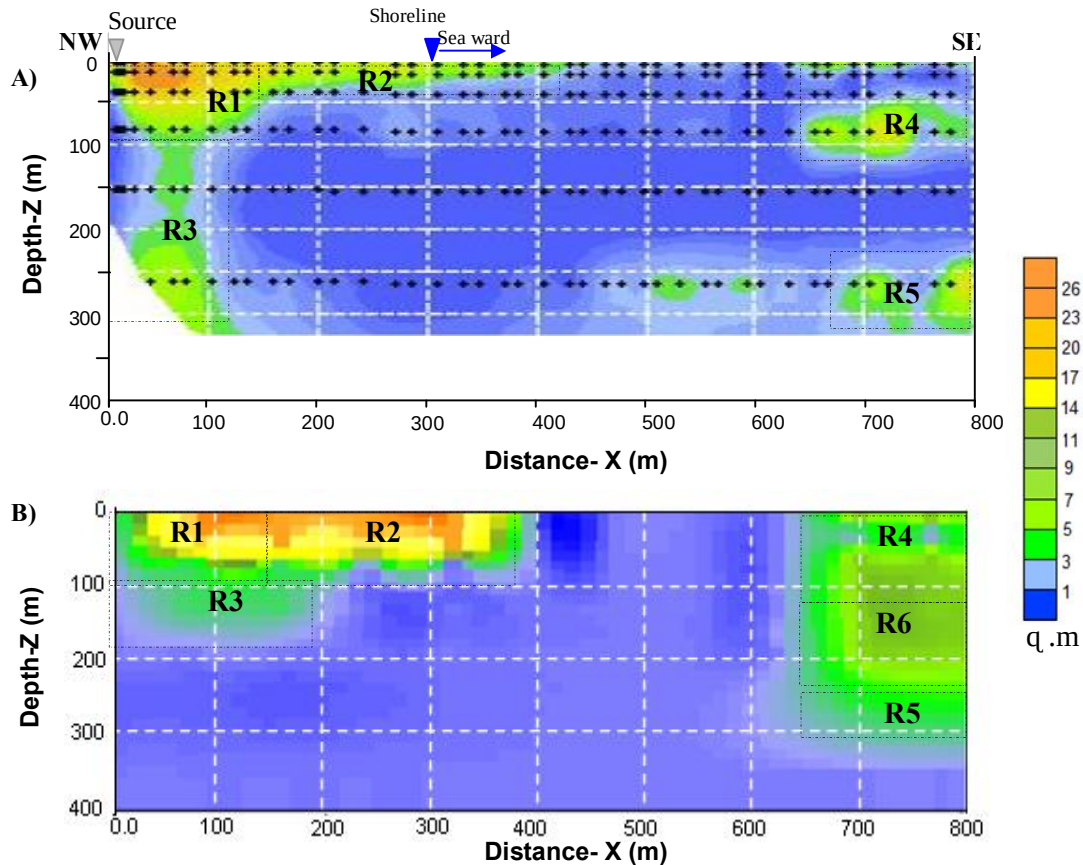


Figure 4.8. Northwest-southeast resistivity structure profiles along the K flight line ($Y = 200$ m), comparing (A) the 1-D inversion model (after Ito *et al.*, 2011) and (B) 3-D model of current study. Color scale of 3-D model changed to fit the color scale used in Ito *et al.* (2011)

4.9. Discussion

The 3-D resistivity model results of the present study show that low resistivity ($< 2 \text{ q-m}$) is characteristic of most of the area beneath both land and sea. A landmass with high resistivity ($3\text{-}25 \text{ q-m}$) extends to a depth of $\sim 100 \text{ m}$ at 80 m seaward from the shoreline to $\sim 300 \text{ m}$ inland. In addition, a resistive structure ($3\text{-}10 \text{ q-m}$) exists to a depth of $\sim 350 \text{ m}$ beneath the beach $400\text{-}600 \text{ m}$ seaward from the shoreline.

previous study in the same area for example, Uehara *et al.* (2007) found a highly resistive landmass of $3\text{-}100 \text{ q-m}$ extending to a depth of 40 m beneath the beach and showed that low resistivity ($< 2 \text{ q-m}$) is characteristic below the highly resistive landmass and adjacent sea bottom. Hayashi *et al.* (2009) reported wellbore logging data from 30 m to 1660 m depths adjacent to our study site (Figure 4.1). Those data indicated that a low-resistivity zone of $1\text{-}2 \text{ q-m}$ exists from 30 m to at least 1000 m in depth.

These previous studies were taken as an evidence present study results. Hence, the following geological features were clarified in the study area. A high-resistivity landmass (sandy ridge) exists down to a depth of $\sim 100 \text{ m}$ underlain by a low-resistivity structure (Quaternary siltstone) which is characteristic of most of the study area beneath both land and sea. In addition, a surficial low-resistivity structure (salt marsh) exists behind the sandy ridge zone, which is thought to be caused by seawater intruding through and beneath the ridges (Figure 4.6).

A near-surface 3-D conductor can cause a sign reversal if the conductor is between the source and the receiver. If the receiver is between the conductor and the transmitter, the voltage curve is shifted to higher amplitudes at early times due to lateral conductivity variations in the surface time-domain EM (Hoerdt *et al.*, 1992). Furthermore, the vertical magnetic field has the largest sensitivity in the near-surface region between the source and the receiver. These sensitivity distributions suggest that the received signals are strongly affected by any anomaly existing between the source and the receiver (Mitsuhata *et al.*, 2002). This phenomenon is recognized in our results as shown in figure 4.8. Namely, in comparison with the 1-D model, the 3-D model showed resistivity structures of larger size that were shifted to depths of several tens of meters in the land side close to the source area; this is attributable to the large electromagnetic field sensitivity distribution in front of the source area. To verify our results I have compared them with Mitsuhata *et al.* (2006)'s results where they reported that on the

land side a high-resistivity surficial zone about 30 m thick is underlain by a low-resistivity ($\sim 1 \text{ } \Omega\text{-m}$) zone. They additionally showed that a low-resistivity structure exists behind the highly resistive landmass. In comparison with our results, these features were also recognized in our study (as shown in Figure 4.9).

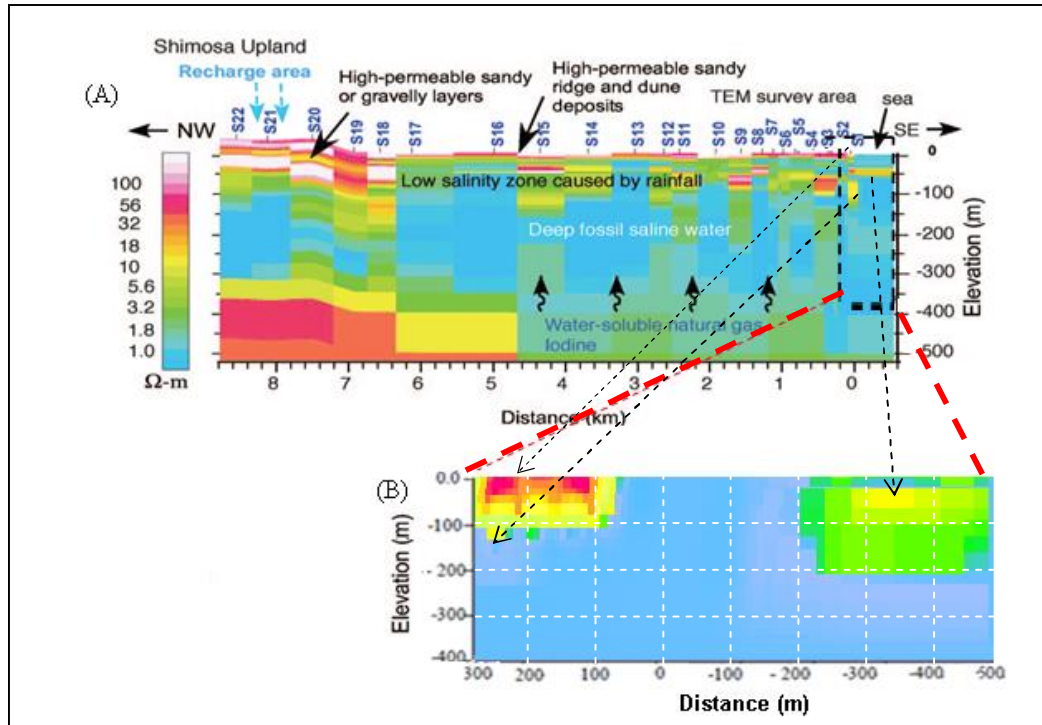


Figure 4.9. Northwest-southeast resistivity structure profiles comparing (A) the results estimated by 2D inversion of AMT (Mitsuhata et. al., 2006) and (B) the GREATEM results along the K flight line (Y = 200 m), at Kujukuri beach area. Shore line is located at X= 0.0 m. Color scale of 3-D model changed to fit the color scale used in Mitsuhata et. al. (2006)

Furthermore, the another evidence for the accuracy of our study results is the Core samples that have been collected at 1m intervals from borehole which have been drilled near the Kujukuri shoreline to investigate the present state of seawater intrusion and the porewater was extracted from each sample (Kiyama and Marui, 1999). Figure 4.10 shows a profile of the electric conductivity of porewater (after Kiyama and Marui, 1999). Since the conductivity of the surrounding seawater is 4500 mS/m, it is inferred that seawater is present both at a shallow depth of approximately 30 m and at depths greater than 160 m. The Kujukuri area is underlain by horizontal sediments that are divided into an alluvial, unconsolidated, sandy formation extending from the surface to a depth of 22 m and an underlying Pleistocene clayey formation, interbedded sandstone

and mudstone. Permeability estimates have been made on the basis of core sample measurements. This confirms the credibility of our 3-D models and the applicability of the GREATEM method to coastal research.

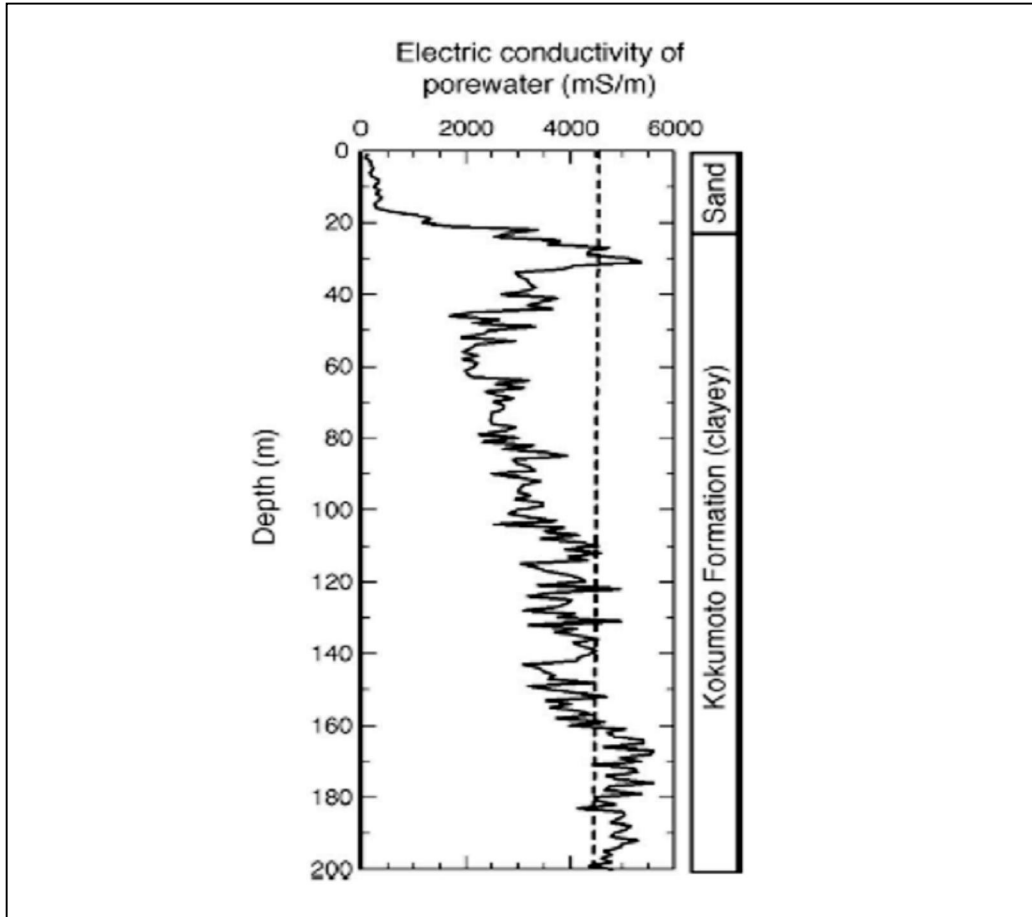


Figure 4.10. Pore-water conductivity profile measured from core samples extracted from borehole drilled near the Kujukuri shoreline (after Kiyama and Marui, 1999). (Modified from Mitsuhashi *et al.*, [2006].)

4.10. Conclusions

The present study results revealed that the GREATEM system can detect resistivity structures in coastal areas down to a depth of ~350 m, within a distance of more than 500 m from the shoreline. The induced current just beneath the source is almost zero and the penetration depth gradually increases with range on both sides of the source. As a result, the GREATEM method has some limitations in that it is difficult to delineate the resistivity structure directly beneath the source, but data quality worsens with increasing distance from the source (Ito *et al.*, 2011). However, the present results show

that the GREATEM system can be a useful tool for studying the characteristics of sea/land boundaries in coastal areas.

The method is also a promising tool for modeling 3-D resistivity structures in coastal areas such as the subterranean distribution of saline water which may lead to land slide or collapse in a volcano edifices and cliff or steep slope along fault (Mogi *et al.*, 2009), as a result, this information can be useful for the study of earthquakes and tsunamis, management of water resources, and development planning in coastal areas. Three-dimensional resistivity modeling that considers large lateral resistivity variations is one recommended solution for the large resistivity contrasts between land and sea in surveys of coastal areas where a 1-D resistivity model that assumes a horizontally layered structure might be inaccurate. Overall, 3-D models are better in recovering the resistivity structures at all depths and can account for lateral conductivity variations.

Chapter 5

Three-dimensional Resistivity Modeling of GRETEM Survey Data from the Nojima Fault, Awaji Island, Hyogo, Southwest Japan

5.1. Introduction

The Nojima fault, Awaji Island, Japan, is located at the NW coast of Awaji Island and is known as source fault of the Hyogo-ken Nanbu earthquake (17 January, 1995; $M_w = 7.2$). The Nojima fault cross cuts the Cretaceous Nojima granodiorite, K-Ar ages of minerals from 70 to 90 Ma (Takahashi, 1992) and cooling age of approximately 74 Ma by the zircon fission track method (Murakami and Tagami, 2004), and its porphyry dykes. Takakura *et al.* (1996) compiled a resistivity map for the northern region of Awaji Island using a DIGHEM type helicopter electromagnetic survey and controlled source magneto-telluric. They found that resistive zones ($>200 \text{ } \Omega\text{m}$) coincide with areas of granitic rocks, whereas conductive zones ($10\text{--}100 \text{ } \Omega\text{m}$) correspond to areas of Tertiary and Quaternary sediment. Many of the known faults in the area were shown as boundaries between resistive and conductive zones. Based on these circumstances, we surveyed the region around the Nojima fault, including the offshore side, and investigated how seawater intrudes into the landside and the effect of the fault on seawater invasion.

The current study was conducted to examine the capability of the grounded electrical-source airborne transient electromagnetic (GRETEM) system (Mogi *et al.*, 1998) for studying coastal areas with complex topographic features. Additionally, this study intended to examine the characteristics of the Nojima fault framework for seawater invasion and the significance of the geological setting around the fault. To enhance the depth of exploration, we used a grounded electrical source aligned parallel to the shoreline and towed a magnetic receiver through the air. The method increases survey depth on both sides of coastal areas, expanding the survey depth to $\sim 1000 \text{ m}$ onshore and to $\sim 500 \text{ m}$ offshore because it galvanically injects electric current into the ground using a large-moment source and a long transmitter-receiver distance. However, the

depth of investigation by current conventional time domain AEM can reach up to 1200 m in case of resistive ground. This study represents the deepest investigation depth by AEM in mapping the subsurface below shallow saline water in coastal areas; this is because the relatively high conductivity of salt water decreases the penetration depth of the AEM signal and tends to shield structures beneath it and often limits geophysical information that can be extracted from the data (Kirkegaard *et al.*, 2011)

5.2. Survey Area Description

Awaji Island, Hyōgo Prefecture, Japan, is located in the eastern part of the Seto Inland Sea between the islands of Honshū and Shikoku as shown in figure 5.1. Many active faults, such as the Nojima fault, Asano fault, Higashiura fault, Kunono fault, Nakamochi fault, Kusumoto faults, and the active fault system of the Median Tectonic Line, are known in the area from Kobe through Awaji Island to northeast Shikoku (Research Group for Active Faults of Japan, 1991). These fault systems are considered to have been active under an east-west compressive stress field since the middle Quaternary (Okada, 1973; Oka and Sangawa, 1981; Sangawa, 1984; Mizuno *et al.*, 1990). The uplift of the Rokko Mountains and Awaji Island and the subsidence of Osaka Bay are known in the Kinki District as the Rokko movement (Ikebe, 1956; Huzita, 1980). A 10.5-km surface fault rupture, the Hokudan Surface Fault Rupture System, appeared along the northwestern coast of Awaji Island after the 1995 Hyogo-ken Nanbu earthquake (Awata *et al.*, 1996). The surface rupture consists of a northeast-southwest right-lateral fault system with a high-angle reverse component. The system has two strands: the 8.8 km Nojima fault and the 3.0 km Ogura fault. Surface displacement is prominent along the Ogura fault and the northern part of the Nojima fault. The maximum displacement along the central part of the North Nojima fault measures 2.5 m (2.1 m of right-lateral displacement and 1.3 m of vertical displacement) (Awata *et al.*, 1998). In contrast, the surface displacement is very small along the southern part of the Nojima fault, where it is parallel with the Ogura fault.

5.3. Previous Geophysical Studies

The geological setting consists principally of Cretaceous granite, which is extensively exposed on the northern part of Awaji Island. Tertiary and Quaternary sediments crop out around the granite near the coast and consist of alternating layers of silt, clay, sand, and conglomerate. Some DC electric and electromagnetic surveys have previously been

completed along the Hokudan Surface Fault Rupture System, as reported by Koreishi *et al.* (1996), Suzuki *et al.* (1996), Takahashi *et al.* (1996), Takakura *et al.* (1996), and the Electromagnetic Research Group for the 1995 Hyogo-ken Nanbu Earthquake (1997). These studies describe two-dimensional (2D) and three-dimensional (3-D) resistivity surveys and very low-frequency magnetotelluric (VLF-MT) surveys in the regions of Hirabayashi, Ogura, and Nashimoto. A resistivity boundary coincides with the surface position of the fault in the Hirabayashi area.

Murata *et al.* (2001) described the stratigraphy and geological cross section along the Disaster Prevention Research Institute, Kyoto University, 500 m borehole drilled into the Nojima fault zone, along which a surface rupture occurred during the 1995 Hyogo-ken Nanbu earthquake. They estimated the vertical component of the displacement and the average slip rate of the Nojima fault based on a structural contour map of the unconformity surface above the basement rocks.

Nishigami *et al.* (2001) deployed borehole seismometers at three depths inside and outside the fault zone along the Disaster Prevention Research Institute, Kyoto University, 1800 m borehole into the Nojima fault zone to estimate the fault zone structure down to seismogenic depths by analysing seismic waves propagating through the low-velocity fault zone, known as ‘‘fault zone-trapped waves’’. The results revealed that the width of the Nojima fault was approximately 20 m and that the velocity and attenuation of S waves (Q value) were approximately 1.0 km/s and $Q = 20$ inside the fault zone and 2.5 km/s and $Q = 100$ outside the fault zone, respectively. Yamaguchi *et al.* (2001) reported the results of VLF-MT surveys, which were made just after ruptures occurred, at six sites across the Hokudan surface fault rupture system to clarify the shallow resistivity structures associated with the ruptures. Their results indicate that the resistivity structure around the Hokudan earthquake system is related to the morphological characteristics of the fault and that conductive zones occur along the faults where surface displacement is prominent. Lin *et al.* (2007) conducted a drilling project through the Nojima fault zone, Awaji Island, to document the effects of the 1995 M7.2 Kobe earthquake recorded within the fault zone. They concluded that the Nojima fault zone contains a damage zone characterized by a network of subsidiary faults and fractures adjacent to the main fault.

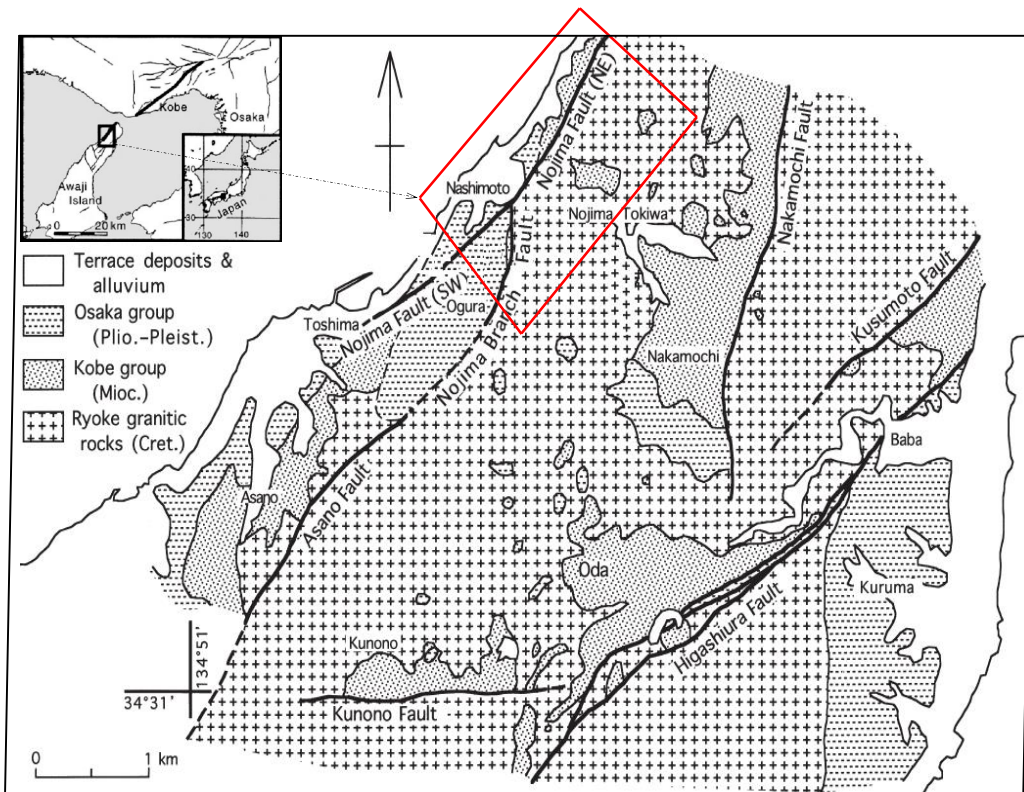


Figure 5.1. The geological map of Northern Awaji Island showing the active faults upon Awaji Island (modified from Murata A. *et al.* [2001]). The red square shows the survey area in the present study.

5.4. Data Acquisition

In the current study, a helicopter airborne survey was conducted along 11 flight lines (A line – K line) both inland and offshore, except for inhabited areas, with a flight speed of 60 km/h. Low-speed flights (40 km/h) were made along J lines, indicated as J2, and tie-line flights, NA1 and NA2, indicated in T1 and T2, as shown in figure 5.2. The low flight speed was used to check the resolution of the survey.

Alternating square wave of approximately 25 A transmitted to the subsurface by a 2.4 km long grounded electrical dipole source set parallel with the shoreline approximately 10 to 50 m inland from shoreline (Figure 5.2). Three components of the secondary magnetic field related to the subsurface resistivity were recorded in the air by a sensor mounted in the bird being towed by the helicopter. The three components data are used in the moving and directional correction, which described at figure 2.4 in chapter 2. After these corrections, corrected vertical time derivative of electromagnetic field component (hz) used in both of 1-D and 3-D modeling. The magnetic field responses

were recorded with the current being both ω ff $\hat{o}$ and ω n $\hat{o}$. The waveforms were digitized through a 16-bit AD converter at a rate of 80 microseconds (μ s), and 20,000 sets of data were recorded during one cycle of 1.6 sec. For flight safety, the bird was flown at a height of about 100 m, and the measured data were subsequently processed to eliminate noise and obtain clearer signal.

5.5. Data Processing

The data reduction procedures flow chart used in this study are the same as those described at figure 2.4 in chapter 2. The obtained results after data processing found to fit with the previous results of other ground geophysical methods in same study areas, which can support the accuracy of data correction and interpretation.

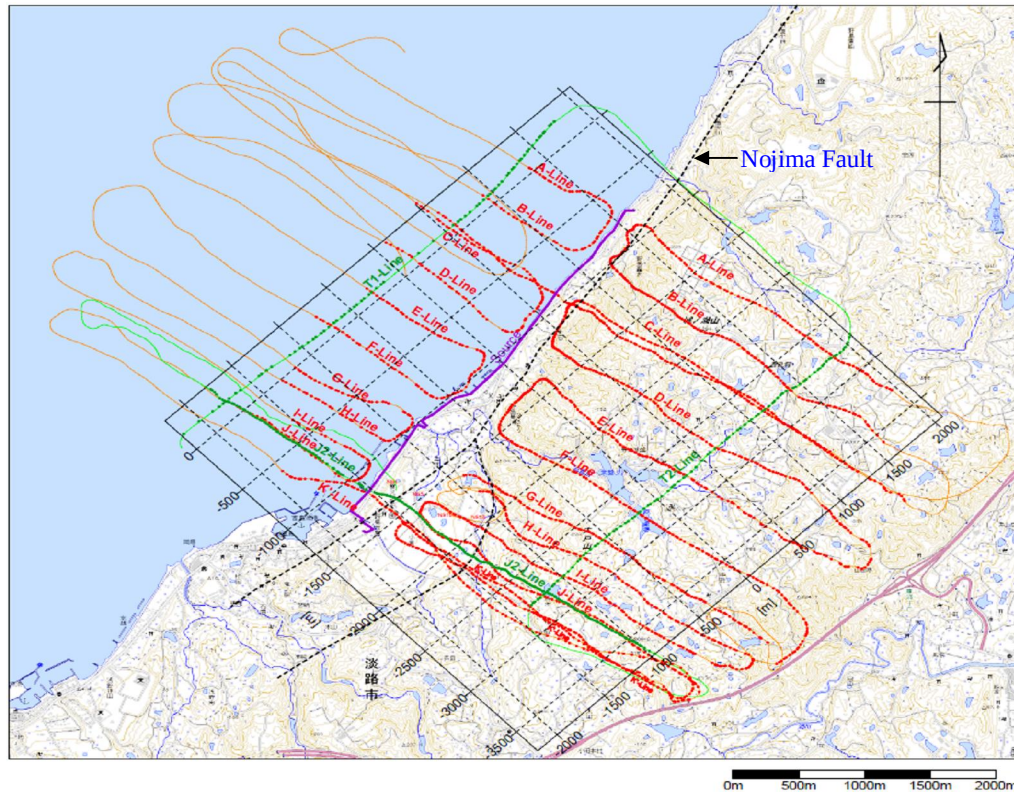


Figure 5.2. The Study area on Awaji Island. Red lines indicate flight lines. The thick purple line indicates the transmitter cable, which was placed 10~50 m inland from the shoreline. The J2 line (green line) indicates low-speed flight lines. T1 and T2 indicate tie lines with normal flight lines. The thicker dots on the flight lines indicate places where clear transient responses used for modeling were obtained.

5.6. One-dimensional Inversion Results

Here I describe the 1-D inversion results after Ito *et al.*, (2012). Figure 5.3 (a and b) shows the northwest-southeast cross sections of the 1-D resistivity structure along (a) flight lines B (easting 1000-1500 m) and (b) H line (easting -1300- -600 m). Both figures clarify a low-resistivity structure of (1-5 $\Omega\cdot\text{m}$) that covers most of the area beneath sea. A higher resistivity structures (30-100 $\Omega\cdot\text{m}$), coinciding with areas of granitic rocks, characterize most of the onshore area. Figure 5.4 shows the northwest-southeast cross section of the 1-D resistivity structure along the flight lines J (easting -1700 - -1000 m) comparing (a) flight line J, with a flight speed of 60 km/h, and (b) flight line J2, with a flight speed of 40 km/h (Ito *et al.*, 2012).

The results show that, a moderate resistivity structure ($\sim 18 \text{ } \Omega\cdot\text{m}$) prevails beneath the surface trace of the Nojima fault, and by applying the low flight speed (40 km/h), subsurface resistivity structures to a depth of 500 m in the offshore can be partly detected by the GREATEM method. However, in contrast, in the case of the 60-km/h flight speed, these structures can be detected only to 300 m in the offshore. Low speed flights can obtain denser data and improve data quality by stacking (Ito *et al.*, 2012).

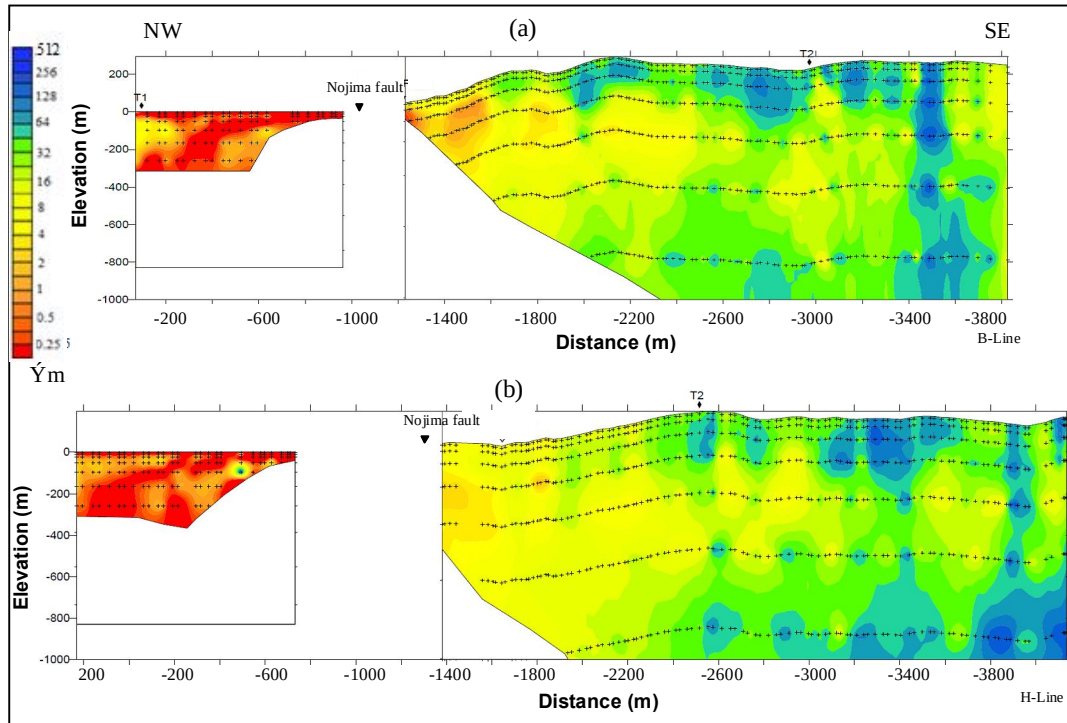


Figure 5.3. Northwest- Southeast 1-D resistivity section along (a) flight line B and (b) flight line H. Black markers indicating the layers boundaries. (After Ito *et al.*, [2012].)

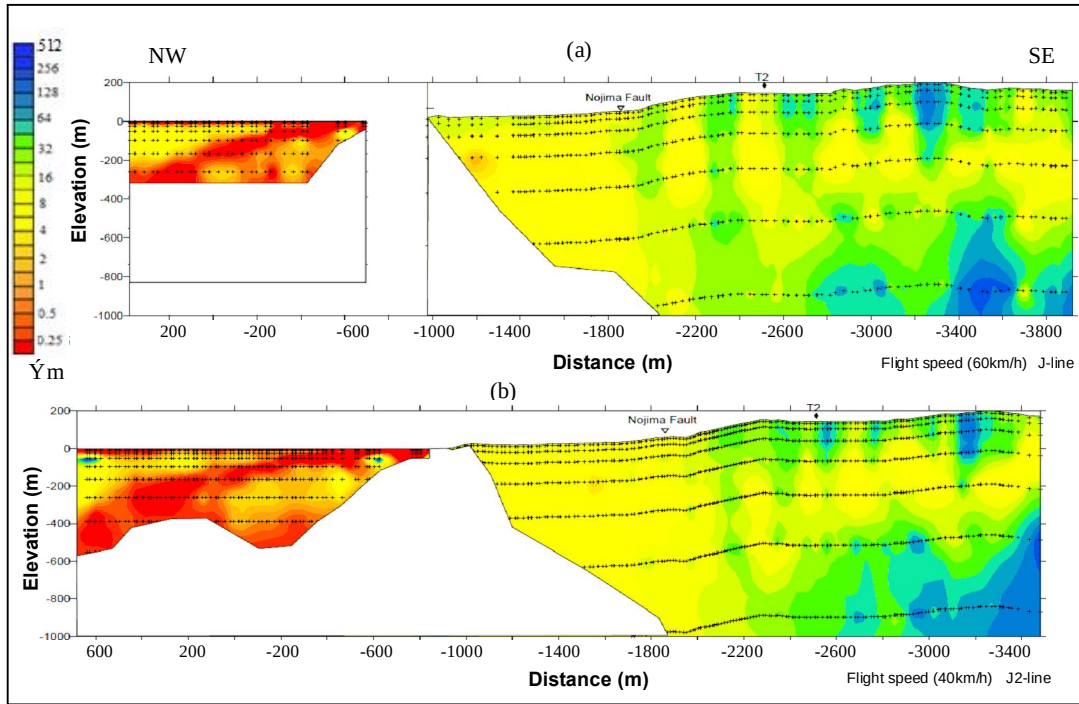


Figure 5.4. Northwest- Southeast 1-D resistivity section along the J flight lines comparing (a) the J flight line with a flight speed of 60 km/h and (b) the J2 flight line with a flight speed of 40 km/h. Black markers indicating the layers boundaries. (After Ito *et al.*, [2012].)

1-D models based on horizontal layers are adequate in many exploration situations, but there are numerous cases such as large resistivity contrast boundaries where 3-D modeling is required (Hoerdt *et al.*, 1992). In this study, the results of 1-D inversion assuming a horizontally layered structure found to fit with the field data, thus the 1-D results are correct under this assumption, however, this is practically not a true case as the subsurface structures are three-dimensional by nature. As a result, in comparison with the resistivity values revealed by other studies in the same area however, the offshore resistivity values revealed by 1-D inversion in present study were acceptable, the onshore resistivity values were found to be much less than the values revealed by these studies. This occurred because the sea has high conductivity, and the lateral conductivity change effects on EM field induction were seriously large at the time of the survey in the coastal area where the source cable was set very close to the shoreline (10-50 m) due to the nature of the mountains and roads in the survey area and there was an appropriate space far from sea. Abd Allah *et al.* (2013a) and discussed at chapter 3 reported the sea effect on EM field induction by GREATEM surveys at coastal areas. They showed that, the sea effect when the source is located 10 m or 20 m landward from the shoreline is much greater than when the source is 300 m from the shoreline.

Therefore, the motivation of this study was to overcome the problem raised by 1-D inversion results through generating a 3-D resistivity model that reflects a real size and tends to have larger conductor size and its contrast to explain observed value, as described in the following sections.

5.7. Three-dimensional Modeling of GREATEM Nojima Field Data

The modified staggered-grid finite-difference method developed by Fomenko and Mogi (2002) and Mogi *et al.* (2011) which is described in the chapter 2 was used to generate a 3-D resistivity structure model of the GREATEM system data from our study area. As shown in figure 5.2, the survey covered a 4 x 4 km square area. The total model size was $x: 35 \text{ km}$ $y: 39 \text{ km}$ $z: 25 \text{ km}$ with a 3-D model domain of $x: 10 \text{ km}$ $y: 11 \text{ km}$ $z: 1.4 \text{ km}$. The model size was gridded into $x: 48$ $y: 57$ $z: 35$ blocks. In the vertical direction, the size of each grid varied from 5 m at the surface to 6400 m at the top and bottom of the model. The horizontal size was approximately 200 m in the modeling area, and large-sized (800~6400 m) grids were added at the circumference of the modeling area to avoid an edge effect. The 3-D model was based on an initial model that consisted of two adjacent onshore and offshore layers of different conductivity, in which a high conductor sea of (10-40 m) depth is placed on top of a sedimentary rocks of varied low resistivity, assuming the presence of a section of topographic structures placed on top of high resistivity granitic rock on the inland side. The offshore resistivity values of the starting initial model were based on the 1-D inversion results. Figure 5.5 shows a section of the model.

The field data were stacked within each grid so that some 3-D effects due to small surface reliefs were averaged out in this grid scale. The transient response curves of the field data were fitted to those computed at the centre of each grid from the 3-D model. I used trial and error methods, so the resistivity values of the initial model were repeatedly changed to obtain the best fit between the 3-D synthetic model and the field data. In the case of the field survey, 10,000 sets of data, digitized at a rate of 80 microseconds (μs), were obtained during a half cycle of 0.8 sec. In the case of the numerical modeling, I used computed transient responses at 30 time channels and 10 time-equal spaces of a log scale in one decade, in the range of 100 microseconds (μs) to 100 milliseconds (ms) (3 decades).

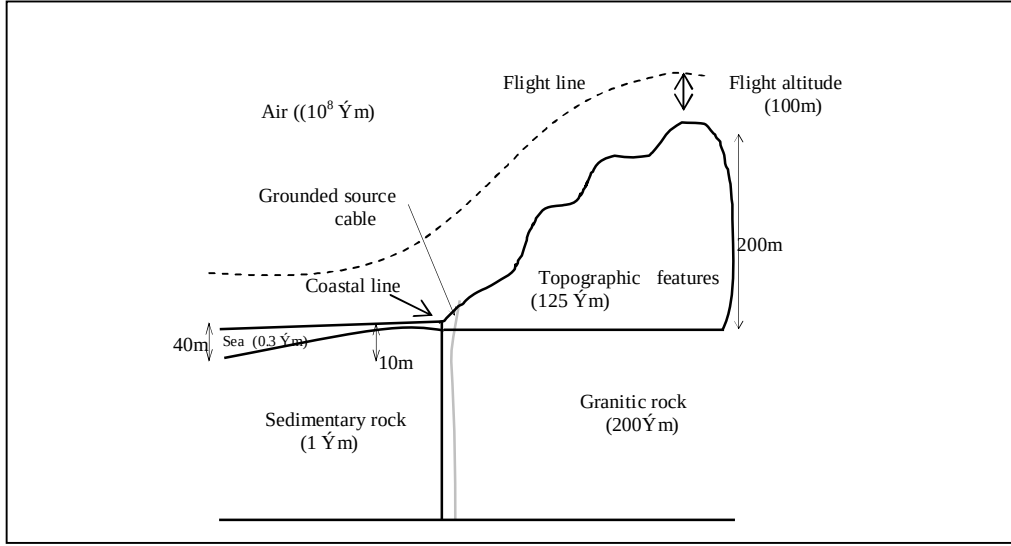


Figure 5.5. The initial model used for the 3-D EM numerical modeling computation. The model consist of two adjacent onshore and offshore layers of different conductivity, such that the sea of (10-40 m) depth is a high conductor (0.3 Ω -m) placed on top of a sedimentary rock of varied low resistivities, and assuming the presence of topographic structure on the inland side placed on high resistivity granitic rocks.

I used only the data of the same time channels (30 sets) and computed the root mean square error (misfit) between normalized intensity by maximum amplitude (dhz/dt) of both field data and modeling responses for different blocks of the 3-D model corresponding to the survey area. The percent root mean-square misfit defined as $[\| \mathbf{E}(\mathbf{d}_{obs} - \mathbf{d}_{cal}) \|^2 / N]^{1/2} \times 10^2$. For the all of the 3-D modeling data, the best fit with field data was found with root mean square error of 2-5% or less. Examples for different fitting RMSE of the model response with field data of good-fit data on flight line B (RMSE = 2%) medium-fit data on flight line H (RMSE = 3%), and not-so-good fitting data on flight line E (RMSE = 5%) are shown in figure 5.6 (A), (B) and (C), respectively. kinks and turns on transit response curves are due to the 3-D effects from horizontal resistivity change. The modeled data that best fit the field data were used to generate the 3-D resistivity model of the study area.

5.8. Three-dimensional Synthetic Modeling Results

Figure 5.7 shows a birds-eye view of the 3-D resistivity structure including topography of onshore side, as well as the geometry of six cross sections which will be shown later. Figure 5.8 shows a northwest-southeast cross section sliced from the 3-D resistivity model along (a) the profile A-A' (Figure 5.7) which is corresponding to the

flight line B and (b) the profile B-Bô (Figure 5.7) which is corresponding to the flight line H.

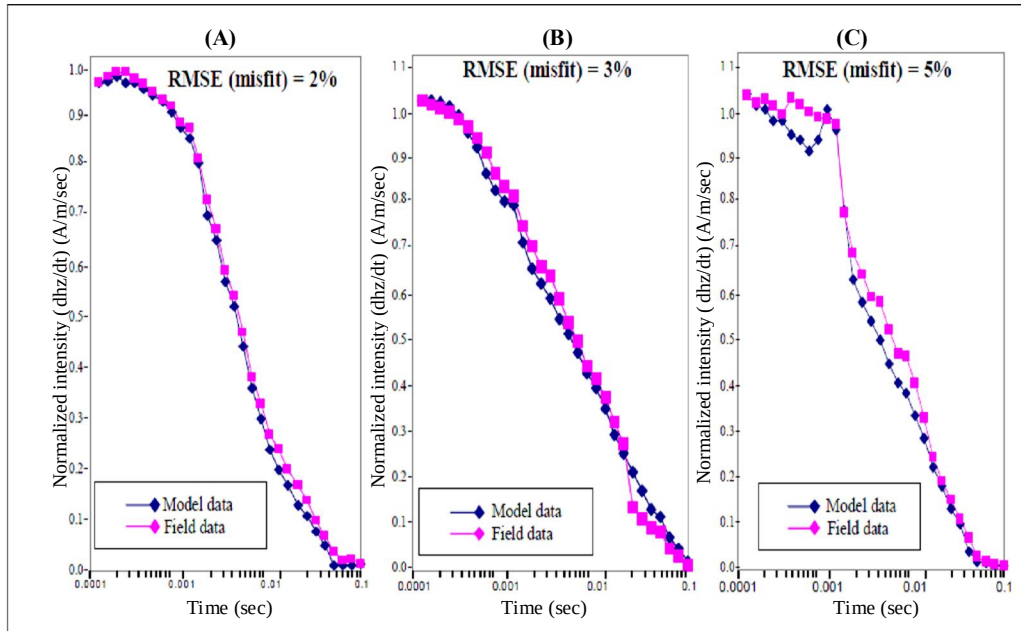


Figure 5.6. Examples of fitting the transient response curves between observed field data and 3-D numerical model data at (A) flight line B (RMSE = 2%), (B) flight line H (RMSE = 3%), and (C) flight line E (RMSE = 5%).

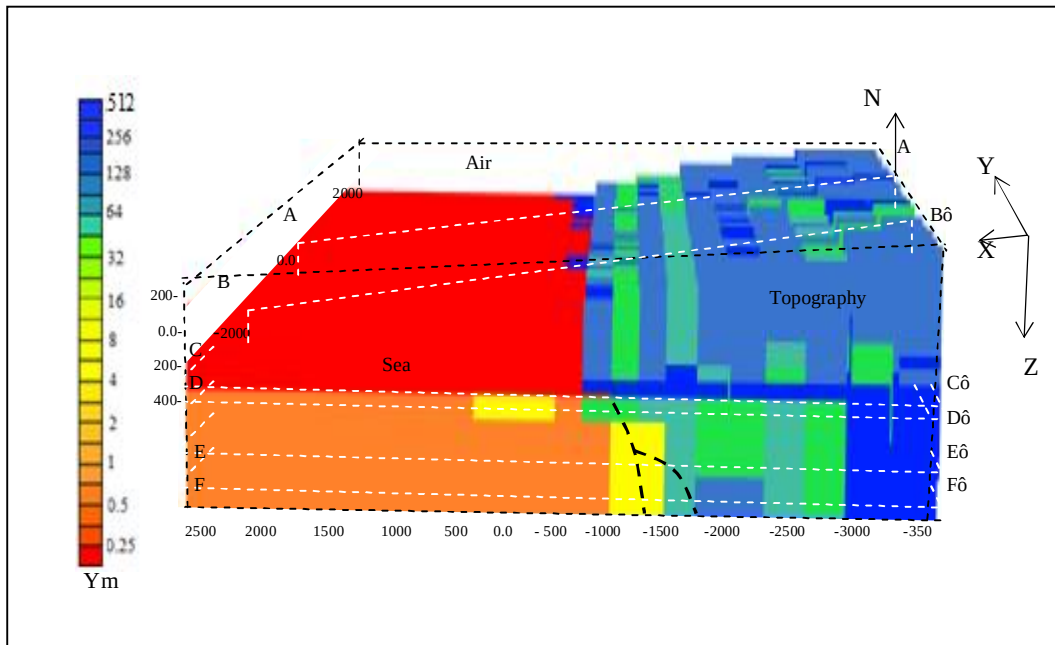


Figure 5.7. Schematic of the 3-D resistivity structure model from the GRETEM data for the Nojima fault area. A-Aô is a resistivity profile along the 3-D model corresponding to the B flight line, B-Bô is a resistivity profile along the 3-D model corresponding to the H flight line. C-Cô D-Dô E-Eô and F-Fô are resistivity profiles along the 3-D model for different depth slices at Z = 0.0 m (near surface), 100 m, 300 m and 500 m respectively.

The results indicate that a highly conductive layer ($<10 \text{ } \Omega\cdot\text{m}$) is dominant beneath the sea in both of the offshore and coastal areas and extends to the Nojima fault at levels deeper than several meters. The onshore area is characterized by high-resistivity structures ($100\text{-}300 \text{ } \Omega\cdot\text{m}$) coinciding with areas of granitic rocks, in addition to a moderate resistivity structure ($50\text{-}75 \text{ } \Omega\cdot\text{m}$), which can be interpreted as a sedimentary deposit. A conductive structure with a resistivity of ($10\text{-}30 \text{ } \Omega\cdot\text{m}$) was also revealed beneath the surface trace of the fault. These models are able to reflect the clear resistivity contrast between the sedimentary and granitic rock which is expected, however there is another resistivity contrast in the onshore area between the structures above sea level and those are below sea level, the reason for that is unknown.

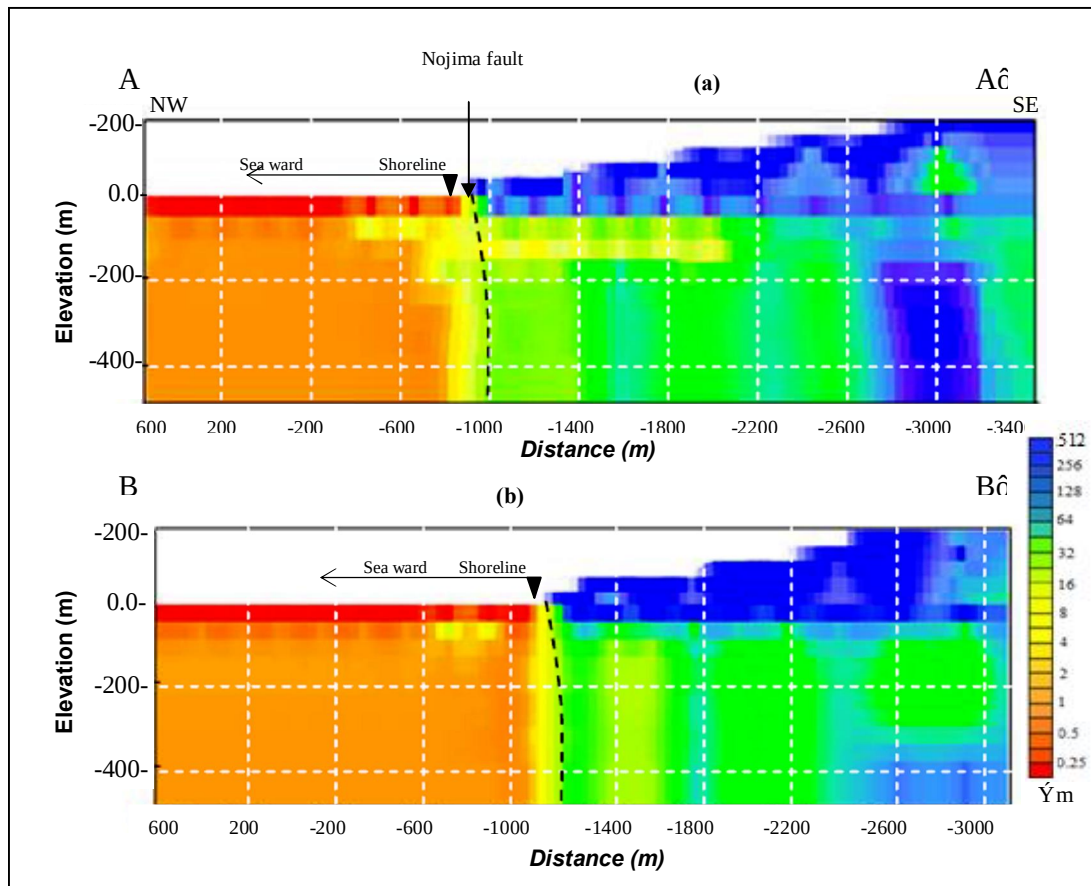


Figure 5.8. Northwest-southeast cross section of the 3-D resistivity model, (a) along A-A' profile (Figure 5.7) which corresponding to flight line B and (b) B-B' profile (Figure 5.7) which corresponding to flight line H.

Figure 5.9 (A, b, C and D) shows a plan view of the 3-D resistivity model at different depth slices, along the profile C-C' D-D' E-E' and F-F' (Figure 5.7) at $Z = 0.0 \text{ m}$ (near surface), 100 m , 300 m and 500 m respectively. As can be seen, from the surface to 500 m

m, a highly conductive layer ($< 10 \text{ q-m}$) is dominant in the offshore area. In contrast, a highly resistive layer ($50\text{-}500 \text{ q-m}$), which coincides with granitic rock and embedded sedimentary deposits, is dominant in the onshore area. The resistivity structure is almost uniform along the fault, but some resistivity variation is seen in the direction perpendicular to the fault strike. The Nojima fault is located at a clear resistivity structure boundary and acts as barrier to sea water invasion.

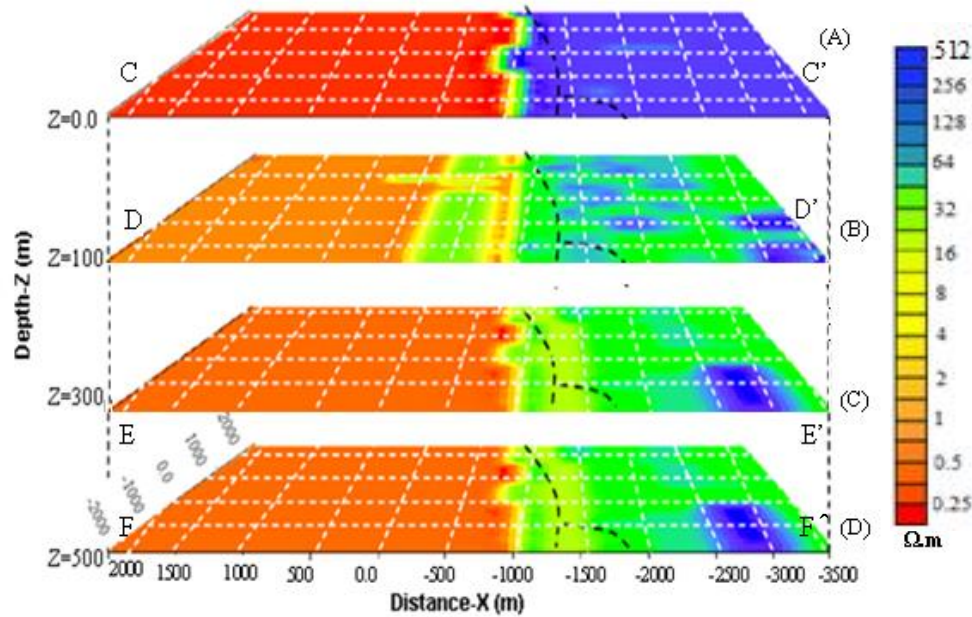


Figure 5.9. (A), (B), (C) and (D) are Plan view of 3-D resistivity model at different depth slices along profiles C-C $\hat{c}$, D-D $\hat{d}$, E-E $\hat{e}$ and F-F $\hat{f}$ (Figure 5.7) at different depth slices at $Z = 0.0 \text{ m}$ (near surface), 100 m , 300 m and 500 m respectively.

The robustness of the resistivity models were tested by computing the 3-D models again, this time with the removal of some resistivity structures, for example removing a 200 m thickness from the offshore resistivity structure ($x = -500 - -700 \text{ m}$) showed in the figure 5.8(a). Removing this thickness from the resistivity structure has significantly increased the global misfit error between the 3-D model response and field data, more than the percentage of measuring data error, indicating the accuracy of the model in these figures.

5.9. Comparison of 1-D and 3-D Resistivity Models

Figure 5.10 shows the northwest-southeast resistivity structure profiles along the B flight line comparing (a) the 1-D and (b) the 3-D inversion models. As we can see, the results of both the 1-D inversion and 3-D resistivity models in the current study clarified that a resistivity structure ($\sim 1 \text{ q-m}$) is dominant in the offshore area beneath the sea. In

the case of the 1-D inversion, a resistivity structure of (30-100 q-m) is characteristic of most of the onshore area. In contrast, in the case of the 3-D model, a resistivity structure of (100-500 q-m) is characteristic of most of the onshore area. The results of the 1-D inversion were not acceptable because the absolute resistivity value onshore was much lower than the true one. We believe that the main reason for the inaccurate was the effect of highly conductive sea on EM field induction at the time of the survey because the source cable was set very close to the shoreline (10-50 m). The 3 D resistivity models were able to reflect the resistivity contrast between sedimentary rock and granitic rock better than 1-D models. Unlike the 1-D inversion results, the 3-D resistivity model results mostly fit with the results of previous studies in the study area, indicating the reliability of the 3-D model.

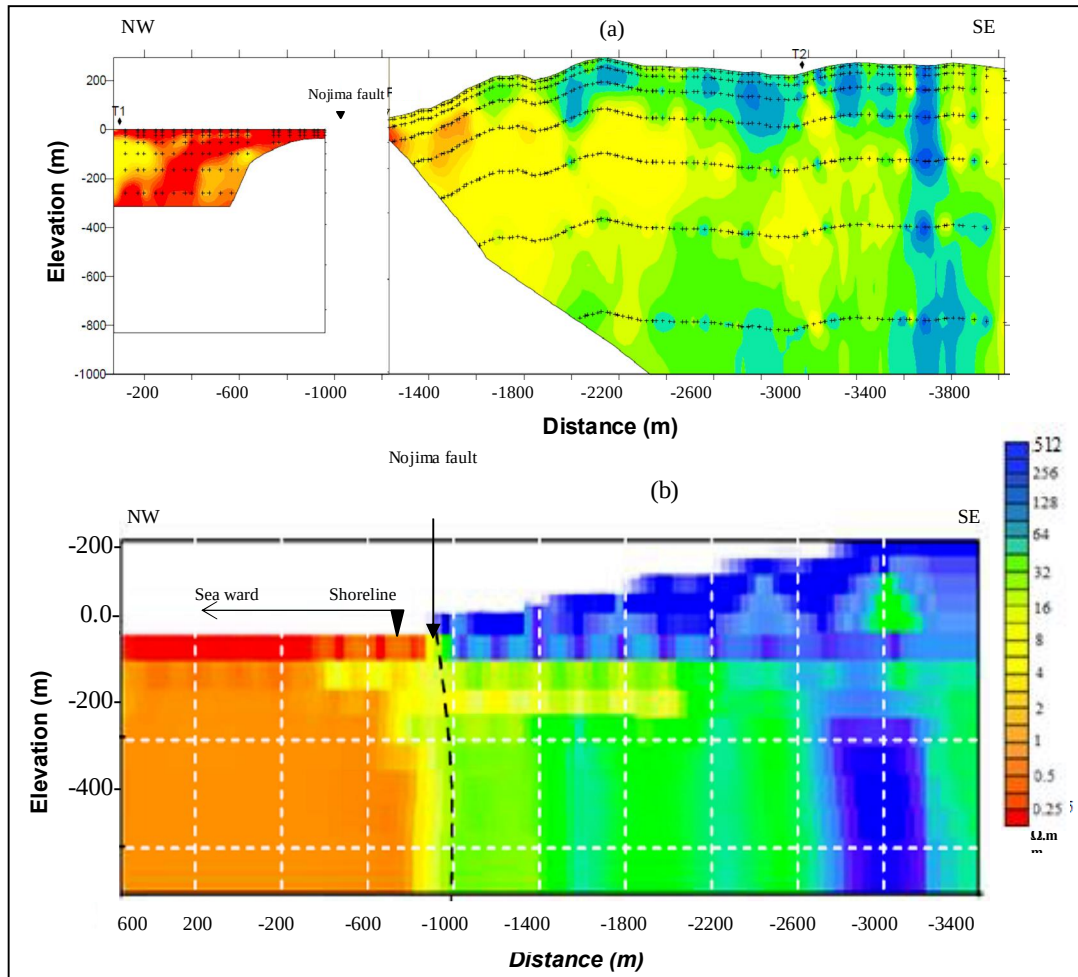


Figure 5.10. Northwest-southeast resistivity structure profiles along the B flight line, comparing (a) the 1-D inversion model and (b) 3-D model.

5.10. Discussion

The 3-D results of the present study clarified that a low-resistivity structure (1-5 Ω -m) is characteristic of most of the offshore area beneath the sea. A moderate-resistivity structure ($\sim 25 \Omega$ -m) is characteristic of the coastal zone between the offshore and onshore areas. Highly resistive zones (100-300 Ω -m) coincide with areas of granitic rocks and are characteristic of most of the onshore area.

Previous studies in the same area showed that the inland side of the Nojima fault is resistive ($>200 \Omega$ -m) and that the coastal side is conductive (10-100 Ω -m) (Takakura *et al.*, 1996). DC surveys in the Nashimoto area by Koreishi *et al.* (1996) and Suzuki *et al.* (1996) revealed an uppermost layer that is moderately resistive (100-200 Ω -m) and about 10 m thick. A moderately conductive dyke structure with a resistivity of (30-60 Ω -m) was also revealed just beneath the surface trace of the Nojima fault.

These previous studies were taken as evidence for reasonable interpretations of the present study results. Hence the following geological features can be clarified in the study area. A highly conductive zone of (1-3 Ω -m), coinciding with Paleogene and Quaternary sedimentary rock, consisting of alternating layers of silt, clay, and sand is characteristic of the offshore area beneath the sea. A highly resistive zone of ($>200 \Omega$ -m) coinciding with granitic rock is characteristic of the onshore area. The Nojima fault acts as a barrier to seawater invasion in the area, as can be seen in Figures 5.8 and 5.9. At very shallow depths (Figure 5.9 A), highly conductive structure which can be interpreted as seawater because it has the same resistivity values of seawater found offshore area, intrudes into the landside area up to the fault zone. At a depth of about 100 m (Figure 5.9 B), less-conductive sedimentary deposits occur in the coastal area. At a depth of about 200 m (Figure 5.8 A), seawater appears to again invade the landside area. Furthermore, an offshore conductive structure ($\sim 5 \Omega$ -m) appears to invade the landside at deeper level of 300 and 500 m (Figure 5.9 C and D).

To verify our results I have compared them with the Takakura *et al.* (1996) result in which they compiled a resistivity map of the northern region of Awaji Island from a helicopter electromagnetic and array controlled source audio frequency magnetotellurics (CSAMT) investigation. They found that resistive zones (200 -1000 Ω -m) coincide with areas of granitic rocks and that conductive zones (10 -100 Ω -m) correspond to areas of paleogene and Quaternary sediments. In comparison with these results as shown in figure 5.11, however the GREATEM results don't recover exact resistivity values of

their study, but in general both of conductive features ($< 100 \text{ } \Omega\text{-m}$) and resistive features ($>500 \text{ } \Omega\text{-m}$) were also recognized in our GREATEM results.

Although the GREATEM 3-D resistivity model results have been improved in comparison with 1-D models results and they overall can reflect the subsurface structure of the area nearly as shown by CSAMT results (Takakura *et al.* 1996) but, their resistivity values are not completely fit with the values revealed by CSAMT study, this maybe because the resistivity section showed by Takakura *et al.* (1996) is located at 1-km northern the B line of our results. Also, maybe due to the effect of high conductive sea on magnetic field induction by GREATEM was large because the source location was very close to shoreline (Abd Allah *et al.*, 2013a). Furthermore, the measured data density of GREATEM is much more than CSAMT case which maybe also another reason.

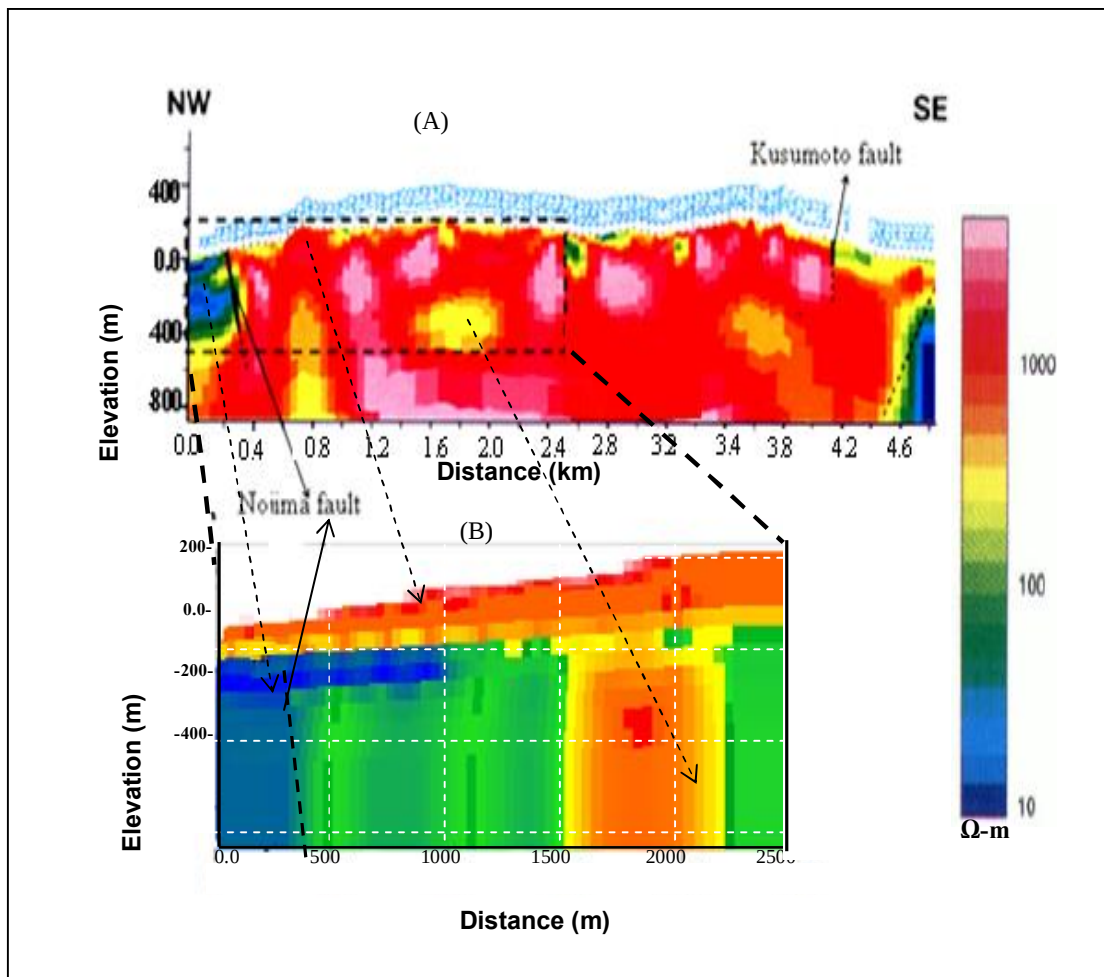


Figure 5.11. Northwest-southeast resistivity structure profiles comparing (A) the results of CSAMT (Takakura *et al.*, 1996) and (B) the GREATEM results along the B flight line at Awaji Island. Coast line is at X=0 m. Color scale of 3-D model changed to fit the color scale used in Takakura *et al.* (1996)

Furthermore, I have compared my results with the Ikeda *et al.* (2000) result in which they showed a resistivity sections of the northern region of Awaji Island from CSAMT investigation. They found that, in the shallower part there is a resistive zones (50 -500 $\Omega\text{-m}$) coincide with areas of granitic rocks and that conductive zones (10 -200 $\Omega\text{-m}$) close to the area of Nojima fault. In comparison with these results as shown in figure 5.12, in general both of conductive features ($< 100 \Omega\text{-m}$) and resistive features ($>200 \Omega\text{-m}$) were also recognized in our GREATEM results. Both of (A) and (B) sections are located close to each other. It should be mentioned that, in case of CSAMT results (A) there is only a few measuring point, so maybe the sensitivity of the GREATEM results (B) is much better due to the dense of the measuring points.

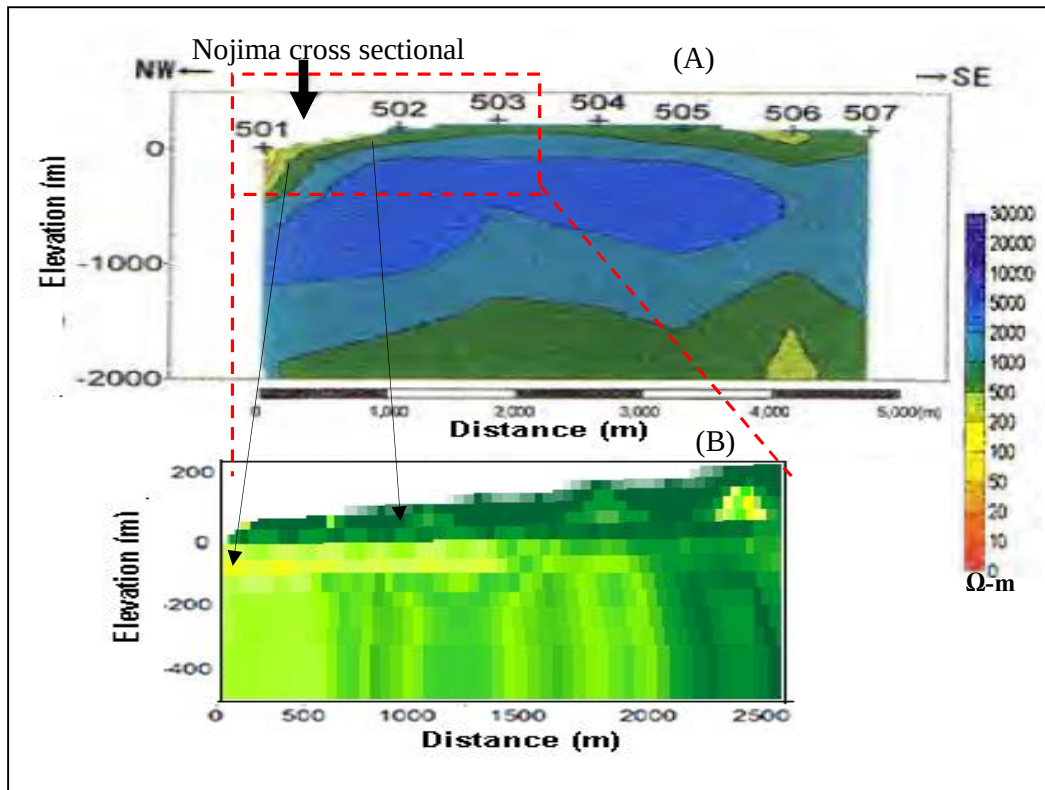


Figure 5.12. Northwest-southeast resistivity structure profiles comparing (A) the results of CSAMT (Ikeda *et al.*, 2000) and (B) the GREATEM results along the B flight line at Awaji Island. Coast line is at X=0 m. Color scale of 3-D model changed to fit the color scale used in Ikeda *et al.* (2000)

Another evidence for the accuracy of our results is clarified in the figure 5.13, which shows the resistivity wellbore logging data from 250 m to 2000 m depths by Ikeda *et al.*, (2000) adjacent to our study site (Figure5.2). Their data indicated that a high-resistivity zone of value ranging from 200 - 3000 $\Omega\text{-m}$ exists from 250 m to at least 1800 m in

depth. At a depth of 300 m the results revealed a resistivity structure (200- 2000 Ω -m) which also revealed by our results at the same depth.

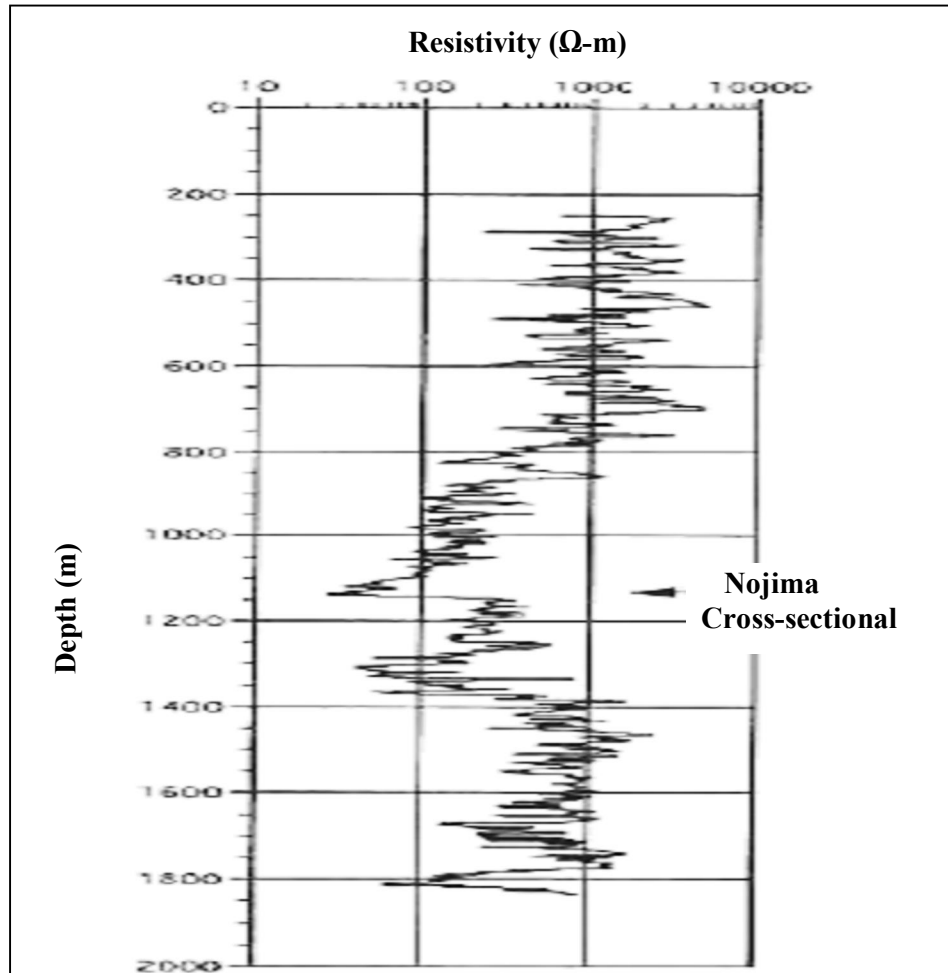


Figure.5.13. Results of the borehole electrical resistivity logging data obtained from well drilling close Nojima fault area. (After Ikeda *et al.*, [2000].)

5.11. Conclusions

In the current study, I obtained a reasonable 3-D resistivity structure around the Nojima fault, which runs along the shoreline. Our results delineated how seawater invades the landside and revealed the fault is a barrier to seawater invasion.

Unlike 1-D resistivity models, the 3-D resistivity model can provide accurate and reliable data, especially at coastal areas where the sea effect on EM induction is significant. The present results show that the GREATEM system can be a useful tool for studying the characteristics of coastal areas with complex topographic features to a depth of several hundred meters. The method is also a promising tool for modeling 3-D resistivity structures in coastal areas, such as sand ridges and subterranean distributions

of saline water. The results reflected that GREATEM can reveal the resistivity structure of the Nojima fault running along coastal areas and this can be useful for delineating a subsurface structure and characterization of an active fault under these situations. As results, this information can be used for the mitigation of natural disasters such as earthquakes and tsunamis, for the management of water resources, and for development and planning in coastal areas.

The current study results fit well with the results of previous studies on Awaji Island, confirming the credibility of 3-D models and assuring the applicability of our method to coastal research. A 3-D resistivity modeling that considers large lateral resistivity variations is required in case of large resistivity contrasts between land and sea in surveys of coastal areas where 1-D resistivity model that assumes a horizontally layered structure might be inaccurate.

Chapter 6

Summary and Future Plans

As a summary of this thesis, the GREATEM geophysical surveys and their 3-D modeling have been shown to be effective in various environmental applications performed at coast and active faults. With an improved signal-to-noise ratio and stronger dipole moments of the transmitters, the variety of GREATEM surveys can be expanded to study groundwater problems and mineral exploration. Conclusions of this thesis are summarized in the following points:

1. I have verified our computing scheme, which is based on the 3-D SFD method (Fomenko and Mogi, 2002) by comparing the results of a quarter-space and trapezoidal hill models with the results of the 2.5-D FEM method developed by Mitsuhashi (2000), and the 3-D SLDM developed by Druskin and Knizhnerman (1994). Although minor differences arise, the main features of the results obtained from the three methods were similar. This confirms the accuracy and credibility of our computing method.
2. The 3-D EM synthetic modeling results in this study indicate that the effect of the sea on GREATEM survey data is inversely proportional to both the distance of the dipole source from the shoreline and 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 closest to the dipole source has a large effect on EM field induction for several meters. The modeling results of this study will be considered when planning future GREATEM surveys, and will be used to provide a reasonable interpretation of data collected in coastal areas. Although it is encouraging that more studies of the effects of sea 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.
3. The GREATEM field survey results at Kujukuri beach revealed that the system can detect resistivity structures in coastal areas to a depth of ~350 m, within a distance of more than 500 m from the shoreline. The induced current just beneath the source is almost zero and the penetration depth increases gradually with range on both sides of the source. As a result, the GREATEM method has some limitations in that it is difficult to delineate the resistivity structure directly beneath the source, but data

quality deteriorates with increasing distance from the source (Ito *et al.*, 2011). However, the present results show that the GREATEM system can be useful for studying the characteristics of sea/land boundaries in coastal areas. The method is also promising for modeling 3-D resistivity structures in coastal areas, such as the subterranean distribution of saline water, which can lead to landslides or collapse in volcanic edifices and cliffs or steep slopes along faults (Mogi *et al.*, 2009). As a result, this information can be useful for the study of earthquakes and tsunamis, management of water resources, and development planning in coastal areas.

4. The results of the second GREATEM field survey at Nojima fault, Awaji Island, were used to delineate a reasonable 3-D resistivity structure around the Nojima fault, which runs along the shoreline. Our results explained how seawater invades the landside. Unlike 1-D resistivity models, 3-D resistivity models can provide accurate and reliable data, especially in coastal areas where the effect of the sea on EM induction is significant. These results indicate that the GREATEM system can be a useful tool for studying the characteristics of coastal areas with complex topographic features to a depth of several hundred meters. The method is also a promising tool for modeling 3-D resistivity structures in coastal areas, such as the subterranean distribution of saline water. The information can be used for the mitigation of natural disasters such as earthquakes and tsunamis, the management of water resources, and development and planning in coastal areas. The results agree with the results of previous studies on Awaji Island, confirming the credibility of 3-D models, and confirming the applicability of our method to coastal research. Three-dimensional resistivity modeling that considers large lateral resistivity variations is required where large resistivity contrasts occur between the land and sea in surveys of coastal areas where a 1-D resistivity model that assumes a horizontally layered structure might be inaccurate.

5. Overall, 3-D models are better for recovering resistivity structures at all depths, and can account for variations in lateral conductivity.

6. Finally, the results show that GREATEM system can give information regarding seawater intrusion in sedimentary rocks and resistivity structure along active faults. These results indicate that GREATEM is a promising method for the assessment of natural disaster areas, such as earthquakes, volcanoes, and active faults, in addition to natural resource management.

Through this research, I would like to propose some future projects that can develop and improve the GREATEM system to increase its efficiency and applicability in various types of research project. Because current 1-D inversion can be distorted in some cases of surveying coastal areas, one research challenge is to complete development of the 3-D EM inversion algorithm for interpreting GREATEM field survey data in other areas with more complex topography (e.g., the Tokachidake volcano, and the Nojima fault area). However, completion of development of this new inversion code is challenging, because little significant research has been conducted relative to the 3-D inversion of Airborne EM systems, but it will make a considerable contribution to that field of study. Furthermore, other research plans include more research studies aiming to improve and develop the GREATEM system, such as increasing the transmitter source moment, as some heli-TEM systems now use a moment of $\sim 10^6 \text{ Am}^2$. This, together with advanced modeling and inversion procedures, can produce quantitative results useful for groundwater modeling in coastal areas, which will expand application of the GREATEM system to investigation of hazardous waste and seawater incursions, and facilitate its use in hydrocarbon exploration.

List of Related Publications

(A) Results Described in Chapter 3.

1. Abd Allah Sabry, Toru Mogi and Elena Fomenko, 2013a, Three-dimensional electromagnetic modeling study of sea and topography effects on EM field induction by grounded electrical source airborne transient electromagnetics (GREATEM) system surveys, Proceedings of the 3-DEM5th international symposium, Sapporo, Japan, May, 2013.
2. Mogi Toru, Elena Fomenko and Sabry Abd Allah, 2011, Three-dimensional modeling of GREATEM data and its application to field data, Proceedings of workshop on recent advances in ground and airborne electromagnetics methods - innovation in processing and inversion techniques. AMD, India, September, 2011

(B) Results Described in Chapter 4.

3. Abd Allah Sabry, Toru Mogi, Hisatoshi Ito, Kazuhiro Tsukuda, Kenzo Kiho, Hideshi Kaieda, Koichi Suzuki, Akira Jymori, Youichi Yuuki and Elena Fomenko, 2013b, Three-dimensional resistivity characterization of a coastal area: application to the Grounded Electrical-Source Airborne Transient Electromagnetic (GREATEM) survey data from Kujukuri beach, Central Japan, Journal of Applied Geophysics, **99**, 1-11,
4. Ito Hisatoshi , Toru Mogi, Akira Jomori, Youichi Yuuki, K. Kiho, Hideshi Kaieda, Koichi Suzuki, Kazuhiro Tsukuda, and Sabry Abd Allah, 2011, Further revealing underground resistivity structures in coastal areas by grounded source airborne electromagnetics, Earth, planet and space, **63**, e9-e12.
5. Abd Allah Sabry, Toru Mogi, Hisatoshi Ito, Kazuhiro Tsukuda, Kenzo Kiho, Hideshi Kaieda, Koichi Suzuki, Akira Jymori, Youichi Yuuki and Elena Fomenko , 2011, Three-dimensional resistivity modeling for the GREATEM survey data at Kujukuri beach, Central Japan, Proceedings for 10th SEGJ international symposium, Kyoto, Japan, November, 2011.

(C) Results Described in Chapter 5.

6. Abd Allah Sabry, Toru Mogi, Hisatoshi Ito, Kazuhiro Tsukuda, Kenzo Kiho, Hideshi Kaieda, Koichi Suzuki, Akira Jymori, Youichi Yuuki and Elena Fomenko , 2014, Three-dimensional resistivity modeling of grounded electrical-source airborne transient electromagnetic (GREATEM) survey data from the Nojima Fault, Awaji Island, South-east Japan, Exploration Geophysics, **45**, 49-61.
7. Abd Allah Sabry, Toru Mogi, Hisatoshi Ito, Akira Jymori, Youichi Yuuki, Elena Fomenko, Kenzo Kiho, Hideshi Kaieda, Koichi Suzuki, Kazuhiro Tsukuda (2013), Three-dimensional resistivity modeling of GREATEM survey data from the Nojima fault, Awaji island, Japan, Proceedings for 11th SEGJ international symposium, 2013, Yokohama, Japan, November, 2013.

(D) Other Publications.

8. Verma K. Saurabh., Toru Mogi, Sabry Abd Allah, Shashi P. Sharma and Elena Fomenko, 2013, 3-D Tau imaging of subsurface conductors by contemporary helicopter born time domain EM systems, Proceedings of the 3-DEM5th international symposium, Sapporo, Japan, May, 2013.

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- Abd Allah S., T. Mogi and E. Fomenko, 2013a, Three-dimensional electromagnetic modeling of sea and topographic effects on electromagnetic field induction by grounded electrical source airborne transient electromagnetics (GREATEM) survey systems, *Proceedings of the 5th International Symposium on Three-Dimensional Electromagnetics Sapporo, Japan*, May 7-9.
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