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Three-dimensional resistivity characterization of a coastal area: Application of Grounded Electrical-Source Airborne Transient Electromagnetic (GREATEM) survey data from Kujukuri Beach, Japan

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ABSTRACT

An airborne electromagnetic (AEM) survey using the Grounded Electrical-Source Airborne Transient Electromagnetic (GREATEM) system was conducted over the Kujukuri coastal plain in southeast 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.

We performed numerical forward modeling to generate a three-dimensional (3D) resistivity structure model from the GREATEM data. This model was developed from an initial one-dimensional (1D) resistivity structure that was also inverted from the GREATEM field survey data. We modified a 3D electromagnetic forward-modeling scheme based on a finite-difference staggered-grid method and used it to calculate the response of the 3D resistivity model along each survey line. We verified the model by examining the fit of the magnetic-transient responses between field data and the 3D forward-model computed data, the latter of which were convolved with the measured system responses of the corresponding data set.

The inverted 3D 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).

1. Introduction

The coast and its adjacent onshore and offshore areas play an important role in local ecosystems, with the mixture of fresh and salt water in estuaries transporting many of the nutrients needed for marine life. Nevertheless, coastal areas are vulnerable to natural disasters such as earthquakes, tsunamis, and hurricanes (e.g., Hornbach et al., 2010; Mallin and Corbett, 2006; Wang et al., 2006). 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, 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

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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 (3D) by nature. Although one-dimensional (1D) models based on horizontal layers are adequate in many exploration situations, there are also numerous cases, such as for overthrusts, salt domes, and anticlines, where 3D modeling is required (Hördt et al., 1992). Here we present a 3D 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.

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 (Fig. 1). The shore-face is barred, with gradients of 1/150 at a water depth of 0–5 m and 1/200 at 5–15 m depth. 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 (Tamura et al., 2008). 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.

We 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 Hayashi et al. (2009), Mitsuhata et al. (2006), and Uehara et al. (2007). Mitsuhata 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.

3. Data acquisition

In the current study, a helicopter-based airborne survey was conducted along 11 flight lines (A–K) spaced 200 m apart (Fig. 1). The survey was performed at both low and high tide to examine whether tide levels affected the results. The difference in seawater levels between the low and high tides was ~1 m over the time span of the survey. 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 (Fig. 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 'off' and 'on.' Only current 'off' time data were used because they were of better quality than those for when the current was 'on'. The waveforms were digitized through a 24-bit AD converter at a rate of 80 microseconds (μs), and 20,000 sets of data were recorded during one cycle of 1.6 seconds (s). 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.

The GREATEM system used in this study was previously used by Okazaki et al. (2011), who described the data reduction method, including noise elimination, in detail. After the corrections for motion-induced, natural and artificial noise, two transient curves induced by opposing current directions were stacked in reverse to cancel out power line noise at frequencies between 50 and 60 Hz.

4. Method

4.1. The GREATEM system

Fig. 2 shows an overview of the GREATEM survey system. The GREATEM system uses a grounded electrical dipole ~3 km long as a transmitting source and a three-component magnetometer in a towed bird as a detector. Mogi et al. (1998) illustrated theoretical transient responses of magnetic fields in the air for horizontally layered structures and noted several features of the GREATEM response, such as the depth of investigation, the effect of the measuring height, and the source–receiver distance. They also highlighted the advantages of the system