Special Section — Marine Control-Source Electromagnetic Methods

2D marine controlled-source electromagnetic modeling:
Part 2 — The effect of bathymetry

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ABSTRACT

Marine controlled-source electromagnetic (CSEM) data are strongly affected by bathymetry because of the conductivity contrast between seawater and the crust below the seafloor. We simulate the marine CSEM response to 2D bathymetry using our new finite element (FE) code, and our numerical modeling shows that all electric and magnetic components are influenced by bathymetry, but to different extents. Bathymetry effects depend upon transmission frequency, seabed conductivity, seawater depth, transmitter-receiver geometry, and roughness of the seafloor topography. Bathymetry effects clearly have to be taken into account to avoid the misinterpretation of marine CSEM data sets.

INTRODUCTION

The marine controlled source electromagnetic (CSEM) method was developed more than 20 years ago to study the electric conductivity structure of the deep ocean lithosphere (Cox, 1981), and has recently found extensive application within the offshore hydrocarbon exploration industry (e.g., Constable, 2006). Most analyses of marine CSEM data have assumed a flat (planar) seafloor, and this approximation has been sufficient for many of the academic applications where signals from seafloor geology are dominant. Early tests of the method for hydrocarbon detection also targeted large reservoirs with a dominant CSEM response (e.g., Eidesmo et al., 2002), but as the commercial application of marine CSEM matures, drilling targets having a much smaller predicted response are being surveyed. In these cases, bathymetry effects in the CSEM response may lead to misinterpretation of seafloor structure, resulting in lost opportunities or misplaced wells. Bathymetry effects on the marine CSEM response have been rarely reported in geophysical literature.

These effects can be simulated by numerical methods. The finite-difference (FD) method is formulated on a rectangular grid, and therefore bathymetry must be modeled as a series of small steps. Um (2005) simulated the marine CSEM response to a vertical cliff using a 3D FD code and suggests that high-quality topographic information should be collected for any marine CSEM survey. MacGregor (1997) distorted the structured finite element (FE) mesh to model seafloor topography, and considered some simple structures, and later MacGregor et al. (2001) incorporated the modified version of the FE code of Unsworth et al. (1993) in an Occam inversion that included topography over a mid-ocean ridge. Unstructured triangular FE are more attractive and more flexible than the FD method for simulating bathymetry effects, because the FE method allows precise representation of bathymetry with the use of a grid that can conform to any arbitrary surface. In the companion paper (Li and Key 2007), the theoretical principles and numerical implementation of the FE algorithm for forward modeling of the frequency domain marine CSEM response over a 2D conductivity structure excited by a horizontal electric dipole (HED) are presented, and the code is validated on a few models. In the present paper, we use this code to specifically study the marine CSEM response to 2D bathymetry.

BATHYMETRY EFFECTS

We consider an upward slope on the seafloor schematically shown in Figure 1. We use a Cartesian system of coordinates: $x$ is strike direction, $y$ is the 2D profile direction, and $z$ positive downwards. The ramp has an elevation of 200 m between 0 and 1000 m in the $y$-direction, i.e., the gradient of the slope is 11.31°. The seawater has a depth varying from $h$ at the bottom of the ramp to $h$-200 m at the top of the ramp. It is assumed that the seawater has a resistivity of 0.3 $\Omega$m, and the sediments below the seafloor are homogeneous with a variable resistivity $\rho$. The HED is located at $(0, -500, \text{and } h-100 \text{ m})$, i.e., at height 100 m above the seafloor.
Numerical modeling is done for both the broadside and inline geometries. In the broadside geometry, the HED is oriented along the $x$-axis (i.e., strike-direction), and the electric and magnetic fields are recorded on the seabed along the $y$-direction. By symmetry, there is no vertical electric field, only an electric component in the strike-direction ($E_x$). As a result, this leaves two nonzero magnetic components, a vertical one ($B_y$) and a horizontal one along the $y$-direction ($B_z$). In the inline geometry, the HED is oriented along the $y$-axis, and the electric and magnetic fields are recorded on the seabed also along the $y$-axis. Thus, there are two components of electric field: a vertical one ($E_y$) and a horizontal one along the $y$-axis ($E_z$). The remaining field is the horizontal magnetic field parallel to the strike-direction ($B_y$).

In the marine CSEM survey, receivers are placed on the seafloor and hence follow the local slope. If a receiver lies on a flat seafloor, it measures the horizontal and vertical components of the electric and magnetic fields. If a receiver lies on a seafloor slope, it measures the electrical and magnetic components along the slope ($E_y$ and $H_y$) and perpendicular to the slope ($E_z$ and $H_z$). The corresponding horizontal and vertical components in the Cartesian coordinate system can be obtained by

$$E_y = E_x \cos \phi + E_z \sin \phi, \quad E_z = E_x \cos \phi - E_y \sin \phi, \quad (1)$$
$$H_y = H_x \cos \phi + H_z \sin \phi, \quad H_z = H_x \cos \phi - H_y \sin \phi, \quad (2)$$

where $\phi$ is a slope angle with respect to the horizontal axis $y$. In the following sections, the horizontal and vertical components of electric and magnetic fields are presented unless otherwise stated.

**Horizontal electric field responses**

Figure 2a and b show the inline and broadside geometry amplitude and phase of the horizontal electric field at a frequency of 0.25 Hz on the bathymetry model (Figure 1) with seawater depth of the ramp bottom $h = 1200$ m and sediment resistivity $\rho = 1 \, \Omega \cdot m$. The amplitude and phase response shows two breaks at 0 and 1000 m, which are coincident with the breaks of the seafloor topography. The inline geometry tangential electric field response ($E_y$) is also shown. From Figure 2a, the difference between the amplitudes of the tangential component ($|E_y|$) and of horizontal component ($|E_z|$) is hardly recognizable. One can see, however, that on the slope ($y = 0 \sim 1000$ m) the phase of the tangential component is about $3^\circ$ smaller than that of the horizontal component. These differences increase with increasing slope angle and hence should be taken into consideration in the interpretation for data sets collected specially in a region with a rugged bathymetry.

One may transform the measured tangential and perpendicular components to the horizontal and vertical components by using equations 1 and 2 before running the modeling.

To highlight the effect on the response of a target, the observed electric field amplitude is often normalized by the data from receivers assumed to be off-target, or by the response of an a priori background electric structure. Here a flat seafloor with a $1200$ m depth seawater layer, underlain by a $1 \, \Omega \cdot m$ half-space, is used as a reference model. The amplitude of the horizontal electric field at the seafloor shown in Figure 2a is divided by the corresponding response at the flat seafloor ($z = 1200$ m) for the reference model and illustrated in Figure 2c. One can see that far away from the ramp the normalized fields for both the inline and broadside geometries overlap each other and approximate one. That is, there is no difference between the electric field of the slope bathymetry and that of a flat seafloor, as the influence of the ramp does not yet appear. Because we are close to
the ramp, the influence of the ramp starts to appear. The normalized fields for both geometries start to deviate from a constant value of one, but in different patterns. The broadside normalized field goes up from that point up the ramp toward the right and reaches a maximum of about 1.051 (i.e., 5.1% anomaly) at about y = 120 m, then it falls down, and this downtrend goes on until the point at the top of the break (y = 1000 m). Beyond this point the broadside normalized field goes up again toward the right. The inline normalized field has two cusp-like anomalies, a minimum of about 0.935 (i.e., negative 6.65% anomaly) at the lower break of the slope (y = 0 m) and a maximum of about 1.105 (i.e., 10.5% anomaly) at the top break of the slope (y = 1000 m). One can see that, on most of the slope, the topographic distortion for the inline geometry is larger than that for the broadside geometry.

Jiracek (1990) clearly demonstrated that the near-surface and topographic distortions in electromagnetic (EM) induction can be described in terms of a galvanic effect arising from the electric charge buildup at the boundary of inhomogeneities, and also an inductive effect. The distorted EM fields can be regarded as a vectorial sum of primary field caused by a background layered earth and secondary field caused by inhomogeneity with the anomalous resistivity $\Delta \rho = \rho - \rho_o$, where $\rho$ is the resistivity of an inhomogeneity and $\rho_o$ is the resistivity of a background structure. In our case, because the ramp and 1D three-layer earth (air layer + 1200 m depth seawater layer + 1 $\Omega$m half-space), respectively, are regarded as the inhomogeneity and a reference model, the ramp has an anomalous resistivity of 0.7 $\Omega$m. Note that the resistivity of seawater is set to be 0.3 $\Omega$m. Assume that the primary electric field points to the right, downward and upward, respectively, over the lower and upper part of the ramp.

Boundary charges form at the boundary of the inhomogeneity, resulting in a secondary electric field that is opposite to the primary field at the lower part of slope and additive to the primary field at the upper part of slope. Hence the total field obtained by a vectorial sum of the primary and secondary fields is reduced at the lower part of slope and enhanced at the upper part of slope. This produces a minimum and a maximum in the normalized field response around the bottom and the top of the ramp, respectively. The magnitude of the galvanic effect is frequency independent. In the broadside geometry, the electric dipole is oriented along the strike-direction, and then the primary electric field might be pointed to the strike-direction too. Hence the electric field in broadside geometry is affected by excessive currents because of the x-directed primary electric field. These currents produce a secondary magnetic field which adds to the primary magnetic field and an anomalous electric field. The amplitude of the inductive effect depends on the frequency. In general, the anomalous electromagnetic field is the result of galvanic charge buildup and of self- and mutual-induction processes (Menvielle, 1988). Note that the normalizing field is the electric field response at the flat seafloor (at $z = 1200$ m) calculated for the reference model; it is different from the primary field that is the electric field along the slope calculated for the reference model. Hence the normalized anomaly is also caused by geometry of bathymetry undulation, i.e., the leveled height difference between the measured site and the corresponding point at the flat seafloor.

The bathymetry effects depend on the slope and roughness of the seafloor topography, especially for the inline geometry. In Figure 3 the normalized inline geometry horizontal electric responses for two other models are shown. In the first model, we simply suppose that the bathymetry has a vertical elevation of 200 m from 1200 to 1000 m at $y = 0$ m (i.e., a vertical cliff). In the second model, the water depth varies smoothly from 1200 to 1000 m with a sinusoidal dependence between 0 and 1000 m in the y-direction, i.e., the bathymetry can be expressed by

$$z = \begin{cases} 
1200 & y \leq 0; \\
1100 - 100 \sin \left( \frac{\pi y}{1000} - \frac{\pi}{2} \right) & 0 \leq y \leq 1000; \\
1000 & y \geq 1000.
\end{cases}$$

The other parameters of both models are the same as those of the bathymetry model shown in Figure 1. For comparison, the response on the upward slope model (Figure 1) is also shown. From Figure 3, one can see that cusps in the bathymetry effect increase with the sharpness of the slope, becoming greatest for the vertical cliff model, and disappearing in the smoothing ramp model. This demonstrates once again that the discontinuity in the inline horizontal electric field responses at both the lower and upper breaks of the slope (in Figure 2) are the result of the bathymetry undulation and not numerical noise.

The dependence of the horizontal electric field response on both the transmission frequency and the seafloor resistivity has been investigated. In Figure 4a and b, the inline and broadside normalized horizontal electric field for different frequencies over the model in Figure 1 with a fixed seafloor resistivity of 1 $\Omega$m is illustrated. One can see that the broadside normalized anomaly depends largely on frequency. In general, the broadside normalized electric field decreases with increasing frequency. At 0.01 Hz, the maximal and minimal anomalies over the slope are 7.9% and 5.2%, respectively, although at 1 Hz they are 4.5% and -4.8%. The inline normalized response is independent of frequency around the lower break of slope, and it varies with frequency around the upper break of the slope and at the right of the slope, in particular for high frequency. These behaviors suggest that the bathymetry distortion in inline geometry is mainly the result of a galvanic effect at the bottom and an inductive effect at the top of the ramp, respectively. Figure 4c and d illustrate the normalized horizontal electric field response for varying seafloor resistivity at 0.25 Hz. The normalized anomaly increases with increasing seafloor resistivity and tends toward saturation.
when the seafloor resistivity is larger than 50 Ωm. This means that the bathymetry is dominated by a galvanic effect for high resistivity below the seafloor.

Figure 4. Dependence of the normalized horizontal electric field on both the transmission frequency (a and b) and the seafloor resistivity (c and d) for the model in Figure 1 with the water depth $h = 1200$ m. The broadside normalized anomaly depends on frequency, although the inline one is independent of frequency around the lower break of slope and dependent on frequency on the upper part of slope; The normalized anomaly tends toward saturation when the seafloor resistivity increases.

Figure 5 shows the broadside and inline geometry horizontal electric field responses for three different seawater depths ($h = 400, 800$, and $1200$ m) in the model in Figure 1. The transmission frequency is

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**Figure 5.** The broadside (left) and inline (right) geometry horizontal electric field for three different water depths ($h = 400, 800$, and $1200$ m) for the model in Figure 1 with the seafloor resistivity of 1 Ωm. Amplitude is shown in the top row and phase in the middle row. The amplitude in (a) and (d) is normalized by the corresponding response of the flat seafloor model with the water depth of $h$ and then illustrated in the bottom row.
Effects of bathymetry on marine CSEM field

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0.25 Hz and the seafloor has a resistivity of 1 Ωm. Airwave dominance can be seen as a flattening of the phase curves at ranges 2000, 3500, and 4500 m, respectively. As the seawater gets shallower, the source-receiver distance where the airwave dominates the seafloor horizontal electric response gets smaller. One can see that after normalization (Figure 5c and f), the effect of bathymetry is the worst for shallower water.

Vertical electric field response

The vertical electric field of marine CSEM method has been rarely studied in the literature, but it is important because it responds to edges of structure (Constable and Weiss, 2006). As stated in the previous section, the vertical electric field $E_z$ exists only for the inline geometry. Figure 6 shows the vertical electric field responses for three different seawater depths ($h = 400, 800$, and $1200$ m) for the model in Figure 1. The transmission frequency is 0.25 Hz and the seafloor has a resistivity of 1 Ωm. These results illustrate that the vertical component of the electric field is distorted by bathymetry. The amplitude and phase response shows two breaks at 0 and 1000 m, where the bathymetric slope changes. Note that, as expected, the phase has a 180° shift at the location of the HED source ($y = -500$ m), where the vertical electric field changes its direction. The airwave effect is not observed on the vertical electric field response because the airwave is always horizontal and does not have a vertical component. However, varying the water depth does have an effect on the seafloor vertical field. In shallow water, the image source above the sea surface is closer to the bathymetry, thus a stronger effect can be observed. In deep water (1200 m), we see a small reduction in the vertical field along the slope followed by an increase with range associated with the shallower seafloor. Because the vertical electric fields for a 800-m water depth are similar, these effects are associated with the bathymetry and not the water surface. However, for a 400-m water depth, the effects of bathymetry on the vertical electrical field are greatly magnified by an interaction with the water surface.

Horizontal magnetic field response

The magnetic field response presents an additional and useful measurement for the marine CSEM method. Figure 7 shows the inline and broadside geometry, horizontal magnetic field response at 0.25 Hz for the bathymetry model (Figure 1) with a seafloor resistivity of 1 Ωm and the water depth on the left side $h = 400, 800$, and 1200 m, respectively. The amplitude of the horizontal magnetic field is normalized by the corresponding value of the flat seafloor model with the water depth equal to that at the HED location (i.e., $h$) and then is shown in Figure 7c and f. It can be seen that the normalized horizontal magnetic field response for the broadside geometry is much larger than that for the inline geometry. Note that different vertical scales in the normalized response (Figure 7c and f) are used for the inline and broadside transmission. The airwave effects on the horizontal magnetic field are observed. As the seawater gets shallower, the airwaves become more significant. In the case with seawater depth of 400 m, the airwaves dominates the horizontal magnetic field response when the horizontal coordinate ($y$) is larger than 700 m, and the bathymetry effect can be barely recognized.

In Figure 8a and b, the frequency dependence of the inline and broadside normalized horizontal magnetic fields for the model in Figure 1 is illustrated, respectively. The seafloor resistivity is 1 Ωm and the water depth on the left side is 1200 m. One can see that the broadside normalized magnetic fields vary with frequency over the whole bathymetry (from the bottom of the slope extending to the right), although the inline normalized responses vary with frequency only at the range $y > 1000$ m and are independent of frequency along the slope. This means that the broadside horizontal magnetic responses ($B_x$) are mainly caused by induction effects, although the

![Figure 6. The vertical electric field response for three different water depths ($h = 400, 800$, and $1200$ m) at 0.25 Hz for the model in Figure 1 with $\rho = 1$ Ωm. (a) Amplitude; (b) phase; (c) the amplitude in (a) normalized by the corresponding data of the flat seafloor model with the water depth of $h$. Airwave effect is not observed on the vertical field response.](image)
Figure 7. The horizontal magnetic field responses for three different water depths ($h = 400, 800,$ and $1200$ m) for the model in Figure 1 with $\rho = 1 \ \Omega \cdot m$. The bathymetry distortion in broadside geometry (left) is much larger than that in inline geometry (right). Airwave effect dominates the horizontal magnetic field response for large source-receiver offset, particularly in the case with 400-m water depth.

Figure 8. Dependence of the normalized horizontal magnetic field on both the transmission frequency (a and b) and the seafloor resistivity (c and d). The broadside normalized response depends on frequency (a), although the inline one is independent of frequency around the lower break of slope and dependent of frequency around the upper break of slope (b). The normalized anomaly tends toward saturation when the seafloor resistivity is larger than $50 \ \Omega \cdot m$ (c and d).
inline bathymetry distortion in the horizontal magnetic field response is caused by the galvanic effect along the slope and by induction effects on the right side of the slope. Figure 8c and d show the normalized horizontal magnetic field response for varying seafloor resistivity at 0.25 Hz. The normalized anomaly tends toward saturation when the seafloor is larger than 50 $\Omega\text{m}$. The similar phenomenon has been observed in the normalized horizontal electric field response shown in Figure 4c and d.

**Vertical magnetic field response**

As stated previously, the vertical magnetic field $B_z$ exists only in the broadside geometry. Figure 9 shows the vertical magnetic field response for three different seawater depths ($h = 400, 800, \text{and } 1200 \text{ m}$) at 0.25 Hz for the model in Figure 1. The seafloor has a resistivity of 1 $\Omega\text{m}$. As with the vertical electric field, the phase of the vertical component of the magnetic field has a 180° shift at the location of the HED source ($y = -500 \text{ m}$), where the vertical magnetic field changes its direction. The airwave effect is observed on the vertical magnetic field response, but it is weaker than that of the horizontal magnetic field and dominates at larger source-receiver offset.

**RESPONSES OF RESERVOIR MODELS WITH BATHYMETRY**

**1D reservoir model**

A 1D resistive layer with a thickness of 100 m and a resistivity of 100 $\Omega\text{m}$ is introduced into the bathymetry model as shown in Figure 10a. The broadside and inline geometry horizontal electric field responses of the 1D reservoir model are computed at a transmission frequency of 0.5 Hz for a HED location at (0, −500, 1100 m). Figure 10b and c shows the amplitude and phase of the horizontal electric field, respectively. One can see that the amplitude and the phase are asymmetric with respect to the HED location, particularly in the inline geometry. The amplitude of the horizontal electric field in Figure 10b is divided by the corresponding values at the flat seafloor for a reference model which consists of the air layer, 1200 m depth seawater layer and 1 $\Omega\text{m}$ half-space, and is shown in Figure 10d. The asymmetry of the normalized responses clearly shows a bathymetry effect upon the marine CSEM results. The survey line on the right side yields smaller normalized response because the seafloor receivers on the right side are further from the 1D resistive layer than those on the left side (Um, 2005). The bathymetry effect for the inline geometry is much larger than that for the broadside geometry.
2D reservoir model

We consider a 2D reservoir model with a finite lateral extent of 5000 m and thickness of 100 m. A simple 2D bathymetry slope is introduced as schematically shown in Figure 11a and b. The horizontal electric dipole (HED) is located at (0, −500, 1100 m). The amplitude and phase of the inline geometry horizontal electric field responses for the 2D reservoir model with both the upward and downward slopes are shown in Figure 12a and b, respectively. For comparison, the electric field responses for the 2D model with flat seafloor topography are also shown. The amplitude of the electric field response is divided by the corresponding values at the flat seafloor for the reference model which consists of the air layer, 1200 m depth water layer and 1 Ωm half-space and illustrated in Figure 12c. Although the model with the upward slope topography produces smaller normalized response than that model without topography change, the model with the downward slope topography produces the largest normalized response. This is because the seafloor receivers on the model with the upward slope topography are further from the reservoir body than those on the flat seafloor model. Similarly, the receivers on the model with downward slope are closer to the reservoir than those without the seafloor topography.

CONCLUSIONS

Bathymetry greatly affects the electric and magnetic field responses measured by the frequency domain marine CSEM method. Model calculations show that all electric and magnetic components are influenced by bathymetry, but to different extents. Bathymetry effects depend on transmission frequency, sediment resistivity, water depth, transmission-receiver geometry, and roughness of seafloor topography. The broadside normalized anomaly depends on frequency, although the inline one is independent of frequency around the lower break of slope and dependent on frequency at the upper part of slope. The normalized anomaly in both geometries tends toward saturation when the seafloor resistivity increases. The inline geometry effect on the horizontal electric field is larger than that for the broadside geometry, whereas the broadside geometry effect on the horizontal magnetic field is larger than that for the inline geometry. The vertical electric field is not affected by airwaves, but because the vertical field disappears at the sea surface, water depth has an effect on the vertical field. In relatively shallow water, the image source above the sea surface is close to the bathymetry, thus can produce large variations in the vertical electric field response.

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