Loop-loop EM inversion and its applicability to subsurface exploration

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Abstract: There are three types of frequency-domain loop-loop EM induction method, depending on the loop separation and their location relative to the ground surface: horizontal-loop EM (HLEM), fixed small-loop EM, and helicopter-borne EM (HEM) methods. Multidimensional inversion provides tomographic images of the subsurface resistivity structure and thus enhances the interpretational accuracy of loop-loop EM data. HLEM method is shown to be effective for exploring groundwater resources in weathered and fractured crystalline basement terrains in semi-arid regions. Also, HEM method is useful for locating weak zones in landslide areas. The applicability of inversion to small-loop EM data depends solely on the S/N ratio. The quadrature response of small-loop EM data can only give the equivalent conductivity of a homogenous half-space model, and thus the in-phase component is essential in inverting EM data. However, the in-phase response is much lower and decreases more rapidly with decreasing frequency than the quadrature response. Further work is needed to obtain conductivity-depth images from small-loop EM data.

1. INTRODUCTION

Accurate estimation of electrical resistivity distribution of the subsurface is often required for mineral and groundwater resource exploration and for geotechnical and environmental investigations. This paper examines the inverse problem of non-invasive characterization of geological heterogeneity using the frequency-domain loop-loop electromagnetic (EM) induction methods. The loop-loop EM methods have a transmitter loop that generates a primary magnetic field and a receiver loop that measures induced magnetic fields caused by interactions of the primary field with the subsurface materials. They include three different types of method depending on the loop separation and their location relative to the ground surface. In the first type of loop-loop EM method, which is referred to as horizontal-loop EM (HLEM), the loop separation is variable and large, say 50 m, and the loop is located about 1 m above the ground surface. The second EM method that I here refer to as small-loop EM method uses fixed coils whose separation is very small, say about 2 m. Recently, a new generation of this type of EM profiling method is gaining popularity for shallow engineering and environmental surveys (Won, 2003). The third method involves helicopter-borne EM (HEM) survey in which the coil separation is about 8 m and the coils are located more than 30 m above the surface. Although the utilities of these EM methods have been demonstrated in many case studies, the interpretation of field data has been mostly limited to qualitative or semi-quantitative analysis often leading to poor model estimation. To accurately characterize geological heterogeneity using these EM methods, one needs an interpretation technique that provides tomographic images of subsurface resistivity structure. In this paper, I show how multidimensional inversion enhances the interpretational accuracy of HLEM and HEM surveys, and also discuss some problems that we may face when applying inversion to small-loop EM data.

2. INVERSION METHOD

The forward modeling used is based on an efficient finite-difference method in which the EM fields are solved on a 3D staggered grid (Sasaki, 2001). To represent geological structures, we divide the model domain into a set of rectangular blocks. Let **m** be the vector denoting the resistivities of the blocks and let **d** be the vector containing the observations from any type of loop-loop EM experiments. The goal of our inversion is to find the model that adequately reproduces the experimental data. To minimize non-uniqueness and assure geological integrity, we seek smooth models and so need to minimize an appropriate objective function which can be stated as

$$\phi(\mathbf{m}) = \left\|\mathbf{W}[\mathbf{d}-\mathbf{f}(\mathbf{m})]\right\|^2 + \lambda^2\left\|\mathbf{Cm}\right\|^2 . \qquad (1)$$

Here, $\mathbf{f}(\mathbf{m})$ are the EM responses predicted by 3D forward theory, **W** is a diagonal matrix whose elements are the reciprocals of the standard deviations of experimental error, **C** is the roughness matrix, and λ is the regularization factor. The inverse problem is iteratively solved by linearizing equation (1) with respect to the initial model $\mathbf{m}^{(0)}$ and searching for a perturbation $\Delta\mathbf{m}$. At the *k*th iteration, the linearized approximation of equation (1) is

$$\phi(\Delta\mathbf{m}) = \left\|\mathbf{W}\left(\mathbf{A}\Delta\mathbf{m} - \Delta\mathbf{d}\right)\right\|^2 + \lambda^2 \left\|\mathbf{C}\left(\mathbf{m}^{(k)} + \Delta\mathbf{m}\right)\right\|^2, \tag{2}$$

where $\Delta\mathbf{d}$ is the difference between the observed and predicted data and $\mathbf{A}$ is the Jacobian matrix. The minimization of equation (2) is equivalent to solving in the least-squares sense the rectangular system

$$\begin{bmatrix} \mathbf{WA} \\ \lambda\mathbf{C} \end{bmatrix} \{\Delta\mathbf{m}\} = \begin{bmatrix} \mathbf{W}\Delta\mathbf{d} \\ -\lambda\mathbf{C}\mathbf{m}^{(k)} \end{bmatrix}, \tag{3}$$

where $\mathbf{I}$ is the identity matrix. The least-squares solution of equation (3) can be obtained using, for example, the modified Gram-Schmidt method.

3. INVERSION OF FIELD DATA HLEM data

HLEM surveys were carried out at many sites in weathered granitic basement in northeast Brazil to locate aquiferous fracture-zones under a thick lateritic overburden. 2D inversion was applied to HLEM data from some representative sites (Sasaki and Meju, 2006). An example is shown in Figure 1. The loops were separated by 50 m and placed 1 m above the earth. The frequencies used are 14080, 7040, 3520, and 1760 Hz. Many of the response profiles in Figure 1a and b show anomalous signatures that are qualitatively similar to the ideal response patterns for dipping conductive dike models. A steeply dipping thin dike-like fracture-zone was predicted at profile position 100 m based on the observed HLEM response pattern. The water production from the borehole at this position is 21000 l/h and is much higher than the typical yield of 2000 l/h found in the region. Although the dipping dyke model may have been helpful in locating such a drilling site, it would not give an insight on how the fracture-zone at this site is different from all the others in the region and why it has the very high water yield. The inversion model in Figure 1c suggests that it is more complicated than a single dipping dyke model. The appearance of the classical signature for a dyke model is mainly due to a zone of enhanced conductivity in the top 20 m at profile position 100 m, which we interpret as the most intensely fractured segment of the weathered overburden. Blow this depth lies a much wider conductive zone that dips towards the far end of the profile. This conductive zone may be interpreted as indicating a stream-recharged subterranean reservoir because a seasonal stream flows crossing the survey line at position 150 m.

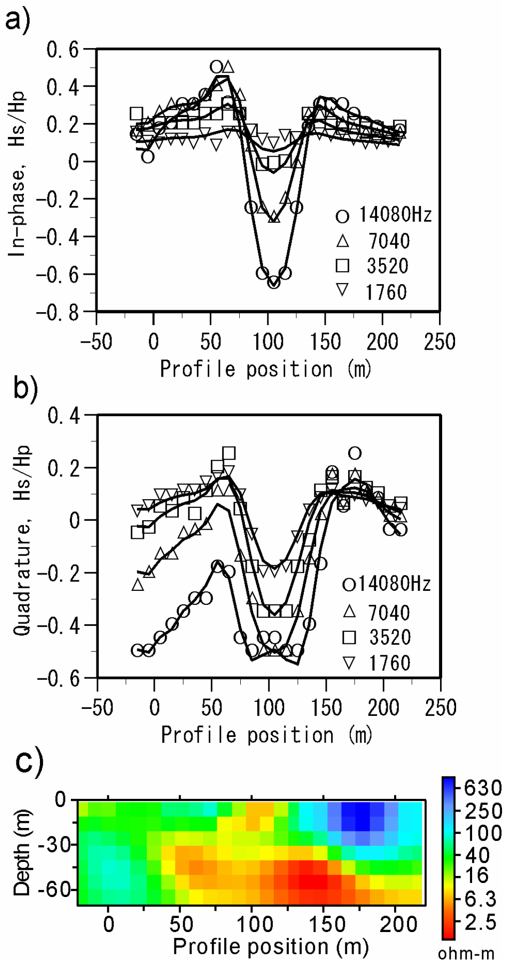

Fig. 1. The fit between observed data (symbols) and those calculated for the model by 2D inversion (lines) is shown for the in-phase (a) and quadrature (b) components. The reconstructed model is shown in (c).

HEM data

A HEM survey was conducted in 2002 over a landslide area in Shikoku Island, Japan. The primary purpose of HEM survey was to assess the utility of the method in defining the resistivity structure associated with landslide masses. The frequencies are 55, 27.5, and 137.5 kHz. Although the data were acquired over a 1 km by 2 km area, our study of field data focused on a single line, which is near and almost parallel to a dc resistivity survey line. 2D inversion result is shown in Figure 2, which agrees basically with the result of dc resistivity inversion shown in Figure 3. The noticeable feature of the image is a conductive zone around locations 600 to 1000 m, which is interpreted as indicating a landslide mass.

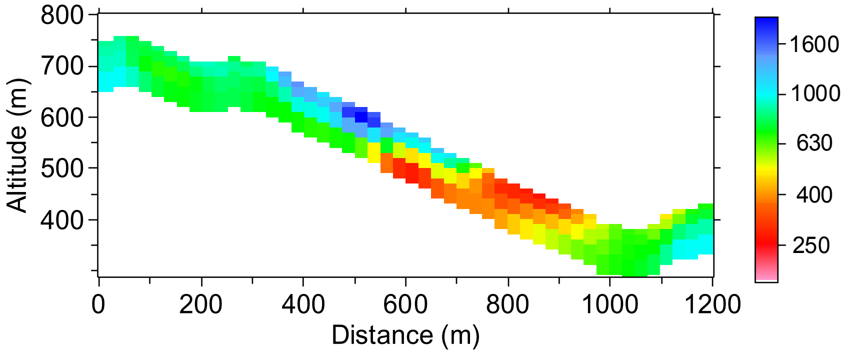

Fig.2. Result of 2D inversion of HEM data over a landslide area.

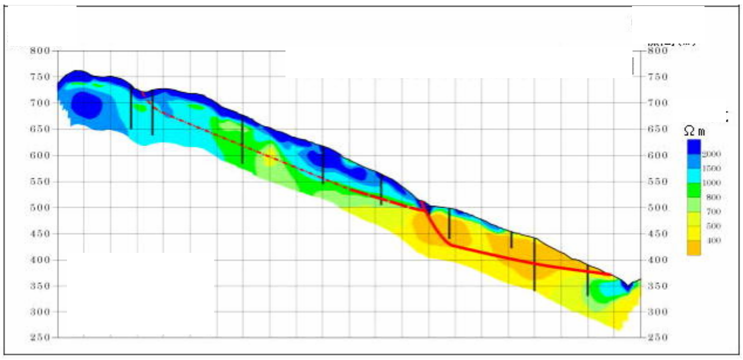

Fig.3. Result of 2D inversion of dc resistivity data. The color scale is different from that in Fig.2.

4. APPLICABILITY OF INVERSION TO SMALL-LOOP EM DATA

Interpretation of small-loop EM data is commonly based on mapping of apparent conductivity derived from measured magnetic secondary field. However, for many applications, information on vertical variation in conductivity structure is called for. Huang and Won (2003) argue that depth sounding by changing frequency is possible with their broadband EM instrument if the subsurface is conductive and show synthetic and field data examples of layered-model (1D) inversion. The fundamental question here is: Under what conditions is 1D inversion applicable? To answer this question, it is important to understand the characteristics of the response of EM method. Song and Chung (2002) show the theoretical sensitivities of a particular EM instrument (GEM-2) to 1D models and discuss the depth of investigation. Figure 4 shows the in-phase and quadrature responses as a function of frequency over a set of two-layer models with variable depths to the layer interface. Notice that the two extreme cases correspond to the responses for homogeneous half-space models with resistivities of 10 and 100 ohm-m. The quadrature responses for two-layer models are almost parallel to those over half-space models. This indicates that it is difficult to distinguish the quadrature responses of the two-layer and half-space models; that is, the quadrature response can only give the equivalent conductivity of a homogenous half-space model regardless of the frequency, which is actually apparent conductivity. Thus, we see that including the in-phase component is essential in inverting EM data for 1D model. However, the in-phase response is much lower and decreases more rapidly with decreasing frequency than the quadrature response. Whether or not 1D inversion is applicable depends solely on the S/N ratio of EM data, which is determined mainly by conductivity structure and ambient noise level.

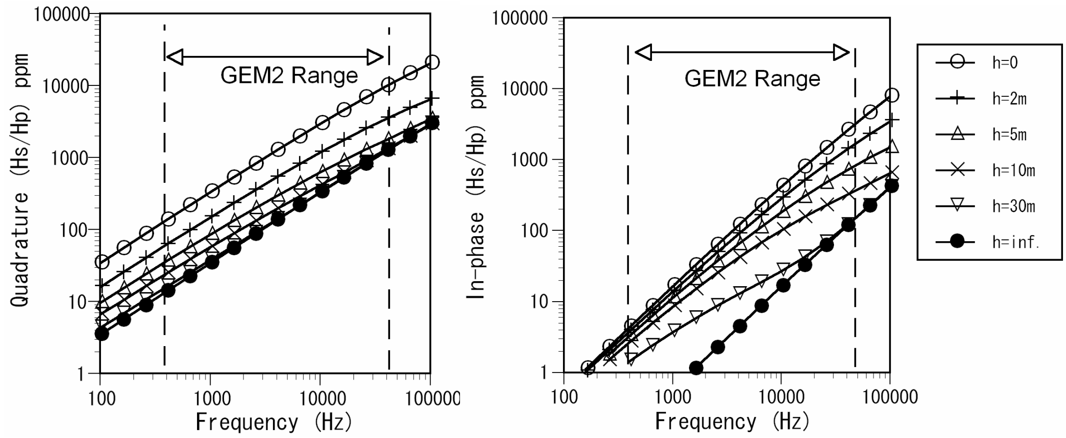

Fig. 4. The theoretical quadrature and in-phase responses of a small-loop EM sensor (GEM-2) as a function of the frequency over two-layer models with variable depths to the layer interface. These responses are the secondary magnetic fields normalized by the free-space primary field and expressed in ppm.

5. CONCLUSIONS

Applications to field data have shown that multidimensional inversion provides an effective means for adequately characterizing geological heterogeneity using loop-loop EM methods. HLEM method will be particularly effective for non-invasive evaluation of groundwater resources in weathered and fractured crystalline basement terrains in semi-arid regions. Also, HEM method can be used to locate weak zones in landslide areas. While multidimensional inversion could be implemented for small-loop EM method, its applicability depends on the S/N ratio of EM data.

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