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Downward-continued pseudo resistivity section using normalized full gradient (NFG) in VLF-EM method

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SUMMARY

Electromagnetic waves with monochromatic or band-limited signals from VLF transmitters would generate secondary induced components of magnetic field due to buried electrical conductivity contrasts. The method, so-called VLF-EM, has been a powerful tool for mapping subsurface geological structures or buried artificial objects because of the cost-effectiveness and of the handiness of surveys that uses only receivers. However, it has not been tested to estimate a pseudo-resistivity section, both the apparent resistivity and the depth of conductive anomaly by using the measured magnetic components with a single frequency. In this study, we introduced the Normalized Full Gradient (NFG) method, generally used for the downward continuation of the potential filed data, for estimating the location and the apparent resistivity in the subsurface using the magnetic components of the secondary induced on the surface. We first simulate a VLF-EM data set for a 2D synthetic model. The cross section of NFG values derived from horizontal component of magnetic field clearly indicates high peaks at edges of a zone of low resistivity anomaly buried in the subsurface. The peak of NFG values from vertical component corresponds with the centre of the anomaly. We then estimated a pseudo-section of apparent resistivity from the VLF-EM data as weighted by the NFG values at each depth. We confirmed that the weighted apparent resistivity takes lower values in the vicinity of the low resistivity anomaly than in the surrounding area, although the estimated value is a little higher than the original. We would like to conclude that our simple technique could give approximate subsurface resistivity structures readily than in the current practice of VLF-EM. Our method could provide an initial model of three-dimensional inversion and would be useful for further geological interpretations.

Keywords: VLF-EM method, potential field, downward continuation, NFG, apparent resistivity

INTRODUCTION

The electrical prospecting (DC resistivity survey) has been generally used to visualize near-surface resistivity structures (e.g., Zohby, 1969). However, we have to put a lot of electrodes in the survey area to carry out this method, and it could become sometimes difficult to acquire high-quality data due to insufficient electrode coupling (e.g., dry surface condition) or to survey limitations by the topography. On the other hand, the VLF-EM method could be carried out readily to acquire tri-component magnetic field of electromagnetic waves. The acquired electromagnetic waves, both the vertical and the horizontal magnetic field due to electromagnetic induction are measured on the surface, are composed of powerful VLF signals transmitted at several locations around the world and the secondary signals generated by the interaction of the VLF signals and the subsurface structure. The latter signals could be used to locate subsurface resistivity anomalies, such as aquifer, active faults, etc.

Recent studies about the VLF-EM methods allow us to estimate the apparent resistivity at a single frequency from the secondary vertical and horizontal magnetic field (Gharibi et al, 1999; Becken et al, 2003). Also, the discrete linear filtering technique (Fraser, 1969; Karous et al, 1983) and the wavelet analysis (Boukerbout, 2003) are effective methods to detect the depth of the anomalies. However, it was difficult to obtain both the information about the depth and the resistivity at the same time without using the complicated inversion techniques. To improve this problem and obtain the underground pseudo-section quickly, we try to estimate the section of the pseudo section of apparent resistivity using the measured magnetic field.

METHOD

In this study, the VLF-EM data set was obtained numerically on a synthetic model. We compute the secondary vertical and horizontal magnetic field at the surface with a single frequency (20kHz) by using a three-dimensional finite difference algorithm. A simple model (such as in Figure 1) is used here. Then, we focus on the Normalized Full Gradient (NFG) method to obtain the depth information of resistivity anomaly. If the potential field satisfy Laplace's equation, the NFG method is generally used for the downward continuation of potential field data. Here, we try to apply the NFG method to the calculated magnetic field. The detail approach is as follwos. First, the the VLF data is convoluted with the function:

$$w(y,z) = \int_{-\infty}^{\infty} e^{iwy+|\omega|z} d\omega \quad . \qquad (1)$$

The downward continuation U of the measured potential H is described as:

$$U(y,z) = \int_{-\infty}^{\infty} H(\xi) w(y-\xi, z) d\xi \, . \qquad (2)$$

To estimate the downward continuation, the fourier transform is applied. Then, inverse fourier transform with weighting estimates U. The NFG operator G is described as follows (e.g., Sindirgi et al., 2008):

$$G(y_i,z_j) = \frac{\sqrt{(\frac{\partial U(y_i,z_j)}{\partial y})^2 + (\frac{\partial U(y_i,z_j)}{\partial z})^2}}{\frac{1}{M}\sum_{i=1}^{M}\sqrt{(\frac{\partial U(y_i,z_j)}{\partial y})^2 + (\frac{\partial U(y_i,z_j)}{\partial z})}} \qquad (3)$$

where M is the number of observation points, $\partial U/\partial y$ and $\partial U/\partial z$ are derivatives of the function U with respect to y and z, respectively. It is important to determine the maximam limit of harmonic in downward continuation process (Dondurur, 2005; Sindirgi et al., 2008; Fedi et al, 2011). We examine the downward continuation field with the NFG operator, which give us te better images of resistivity anomaly.

Our aim is not only estimation of depth of anomalies but also the evaluation of pseodo-section of apparent resistivity. As indicated in Gharibi and Pedersen (1999) by using the secondary vertical and horizontal magnetic field measured at the surface, we can compute the impedance and the apparent resistivity along the y-axis employing two following equations,

$$Z_{xy}(y) = Z_{xy}(0)\frac{H_y(0)}{H_y(y)} + \frac{\int_0^y i\omega\mu_0 H_z(y_0)dy_0}{H_y(y)} \qquad (4)$$

$$\rho_a(y) = \frac{1}{\mu_0\omega}\left|Z_{xy}(y)\right|^2 \qquad (5)$$

where μ_0 is the magnetic permiability of free air, and ω is angular frequency. The apparent resistivity in Eq (4) is for the surface. For estimation of apparent resistivity at a depth, we multiply the computed magnetic field by the NFG operator and substitute the new magnetic field for Hy and Hz in the Eqs.(2) and (3). Here, we call the cross section with the weighted apparent resistivity as "pseudo-resistivity section".

For numercial simulation, we assume the resistivity model as shown in Figure1. This model has background resistivity 1000 ohm-m. A resistivity anomaly of 100 ohm-m is imbedded in a model with the width of 60m and a thickness of 10m.

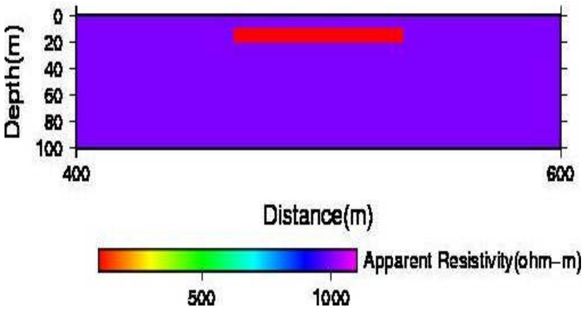

Figure 1. A model of subserface resistivity structure

RESULTS AND DISCUSSION

The NFG value indicates the location of resistivity anomaly well. Figure 2 and 3 show the results of the NFG applying to Hy and Hz measured at the surface. As you can see, it is confirmed that the location of a resistivity anomaly is detected by controlling the harmonic limits in the downward continuation process. Note that, the harmonic limits has a relationship with the resolution for the anomaly below the surface. If we choose the proper maximum limit of the wavelength similar to the anomaly's depth, we can detect the correct location of the resistivity anomaly. For example, in the case that the anomaly is buried at the deprh of 10m, NFG values and an proper high NFG area overlapping to the assumed anomaly is obtained if we choose the harmonic limit as 50. Also, figure 2 shows that the NFG from the horizontal magnetic field can determine the both edges of the anomaly. Figure 3 shows that the NFG from the vertical magnetic field can detemine the center of the anomaly.

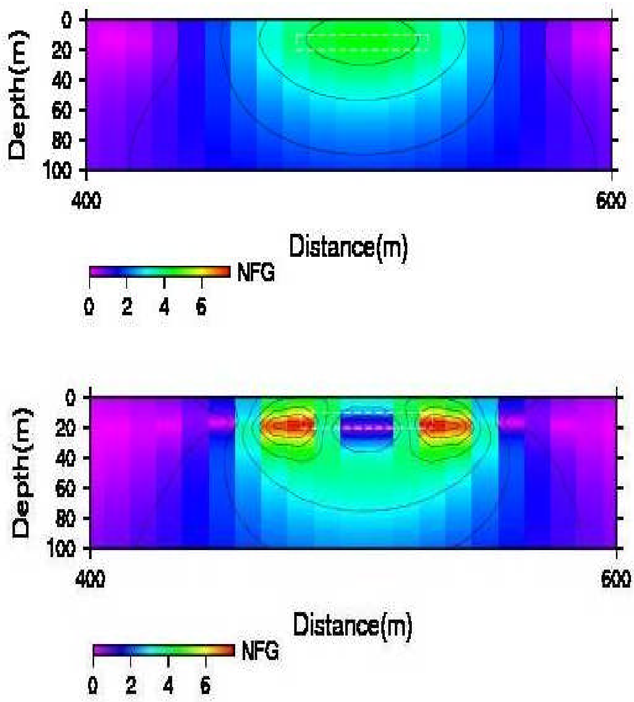

Figure2. Cross section of the NFG applying to Hy (top: harmonic limit = 17, bottom: harmonic limit = 50). The bottom one show the clearer contour map, while the top one show ambiguous image judging from the NFG value and the contour lines.

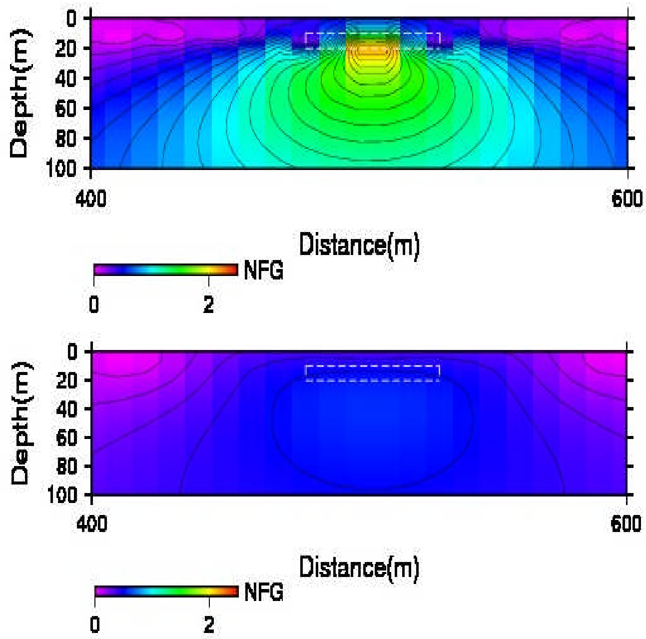

Figure3. Cross section of the NFG applying to Hz (top: harmonic limit = 17, bottom: harmonic limit = 50). The bottom one show the clearer contour map, while the top one show ambiguous image judging from the NFG value and the contour lines.

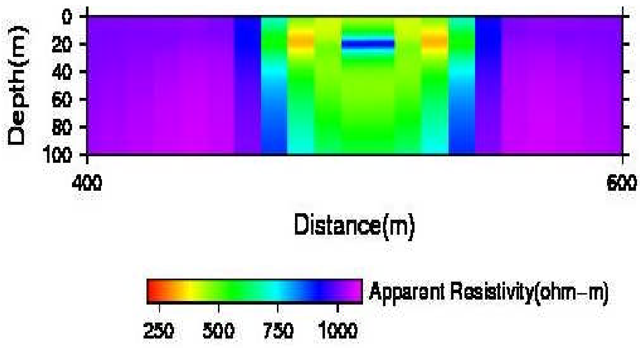

Figure4. An estimated pseudo-resistivity section

We also obtained the pseudo-resistivity section, similar to the assumed model. Figure 4 shows the estimated cross section of apparent resistivities. It is confirmed that the estimated apparent resistivity is lower around the assumed anomaly. However, the higher apparent resistivity value is obtained at the centre of the resistivity anomaly, owing to the effect o f the NFG value . Also, the background resistivity is imaged higher than the original one.

CONCLUSION

In this study, we introduced the NFG method to the analysis of VLF-EM data set for imaging the subsurface apparent resistivity distribution. After the application of the NFG method, it turned out possible to detect the both edges of the anomaly from horizontal magnetic components, and the center of the anomaly from the vertical magnetic components. Pseudo-resistivity section was then estimated from the measured magnetic fields on the surface for a single frequency signal. Although our NFG-guided estimation gave a little blurred distribution of low resistivity anomalies, The pseudo-resistivity section could be used for building an initial model for inversion for three-dimensional resistivity structure.

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