Z-99 ELECTROMAGNETIC FIELDS IN A NON-UNIFORM STEEL-CASED BOREHOLE

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Abstract: Since most oil wells are cased with steel pipes, electromagnetic (EM) signals undergo a severe attenuation as they diffuse across the casing. This paper presents the effect of non-uniform casing properties on EM fields measured in a steel-cased well embedded in a layered formation. We use a finite-element method to compute secondary azimuthal electric fields for a cylindrically symmetric conductivity model, while primary fields are analytically obtained for a homogeneous casing in a whole space. Although EM signals induced by a layered formation are greatly masked by the steel casing, phase responses are more pronounced than amplitude responses. The effect of casing non-uniformity is quite large but highly localized. When the conductivity rapidly varies in the casing wall, the resulting EM fields also fluctuate rapidly. These fluctuations are so similar that their cross correlation function is strongly peaked at two points, whose distance is equal to the separation between source and receiver. The high-frequency coherent noise caused by the non-uniform casing event can be largely suppressed by low-pass filtering to enhance EM signals from the formation conductivity.

INTRODUCTION

Most oil wells are cased with pipes except for exploratory and freshly drilled wells. Carbon steel is the most commonly used material for the pipes (Wu and Habashy, 1994). Since steel casing is typically eight orders of magnitude more conductive than the formation around the borehole (Nekut, 1995), electromagnetic (EM) signals from the surrounding formation undergo a severe attenuation as they transmit across the casing.

Uchida et al. (1991) showed that casing attenuation effects become impractically large at frequencies above several hundred hertz. Low-frequency measurements are an effective means of isolating a formation response from a casing response. Wilt et al. (1995) suggested that the steel casing effect was localized within the pipe section including EM sensors and could be separated from EM responses of the formation. Kirkendall et al. (1999) showed the casing effect on an induction coil is limited to less than 0.3 m above and below the coil. Lee et al. (2004) confirmed the localization of the casing effect through numerical modeling of steel casing with collar.

In addition to the attenuation effect of casing, the non-uniformity of casing materials will complicate data interpretation. Three properties of the casing are particularly important in determining EM behavior in a cased well: electrical conductivity, magnetic permeability, and the thickness of casing wall. Wu and Habashy (1994) showed that the thickness of steel casing does not vary significantly and that the electrical properties would most affect EM fields.

To investigate the effect of steel casing efficiently, Lee et al. (2004) developed an accurate but simple finite-element modeling (FEM) scheme to simulate EM fields in a medium of cylindrically symmetric conductivity structures. We further extend their modeling scheme to include an inhomogeneous casing embedded in a layered formation. This extension also involves the use of FEM to account for signal propagation through casing wall. In this paper, we seek a possibility to detect EM signals from the surrounding formation through inhomogeneous steel casing.

CASING EFFECTS

EM induction techniques are commonly used to measure the resistivity distribution in the vicinity of a borehole. However, most boreholes are cased with carbon steel, and estimation of the effect of such steel casing on the EM induction is difficult. To investigate the effect of steel casing we select a model as showing in Fig. 1, consisting of a steel-cased well embedded in a cylindrically symmetric earth. A conductive disk-shaped layer of 2 S/m exists in a uniform whole space of 0.2 S/m and is the target layer to be detected through casing measurements. The radius and thickness of the disk-shaped layer are 20 m and 5 m, respectively. The casing has an electrical conductivity of $\sigma_c = 10^6$ S/m, magnetic permeability of $\mu_c = 6.25\mu_0$ ($\mu_0 = 4\pi \times 10^{-7}$ H/m), with an inner radius of 0.1 m and wall thickness of 0.01 m. The source used is a loop of wire of 0.1 m diameter carrying 1 A current at 100 Hz. Vertical magnetic H_z fields are measured in the cased well.

Fig. 2 shows normalized amplitudes (left) and phase differences (right) of H_z fields for the uniform casing model shown in Fig. 1. The offset distance between source and receiver is set to 1, 2, 3, 4, and 5 m. In the illustration, the H_z field is plotted at the center of source-receiver offset. The primary H_z^p field, which can be analytically calculated (Song and Lee, 1998), is the H_z field that would be observed in the cased well embedded in the uniform 0.2 S/m whole space. The phase difference means the difference between phases of H_z and H_z^p. From the figure we can find EM anomalies due to the 2 S/m conductive layer although these magnitudes are quite small. Negative phase anomalies become large as the offset is increased. In contrast, amplitude responses are relatively complicated and the maximum amplitude appears at the 2 m offset.

The most significant limitation of borehole EM concerns the difficulty of interpreting data acquired through wells cased in carbon steel, the most common steel used in the oil patch. Even a small change of casing properties may yield a very large variation of EM fields measured in the cased well. In order to investigate this effect we slightly modify the model shown in Fig. 1 to include a small inhomo-geneous part into the steel casing. The inhomogeneous part, 10 cm long and 0.25 cm thick, is located in the outmost region of the casing wall and has 10 % lower conductivity ($0.9\sigma_c$) and/or magnetic permeability ($0.9\mu_c$) than the surrounding casing wall. We locate this inhomogeneity at 2 m above and below the upper boundary of the conductive layer. The loop current source is fixed at $z = -10$ m.

Fig. 3 shows normalized amplitudes (left) and phase differences (right) of H_z fields for the non-uniform casing. The H_z field is plotted at the receiver depth. As expected, the effect of casing non-uniformity is quite large. This is more apparent in amplitude responses than in phase ones. In the am-

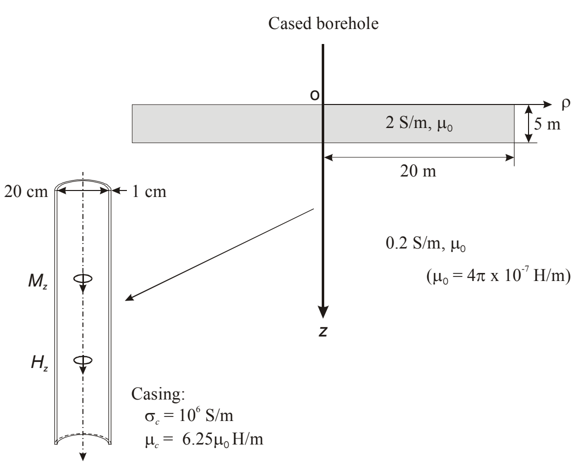

Fig. 1. A cylindrically symmetric earth model with a steel-cased borehole. A conductive disk-shaped layer of 2 S/m, its radius and thickness are 20 m and 5 m, respectively, exists in a uniform whole space of 0.2 S/m. The electrical conductivity, relative magnetic permeability, inner radius and wall thickness of the casing are 10^6 S/m and 6.25, 0.1 m and 0.01 m, respectively. Both a loop of current source and a vertical magnetic sensor are inserted in the cased borehole.

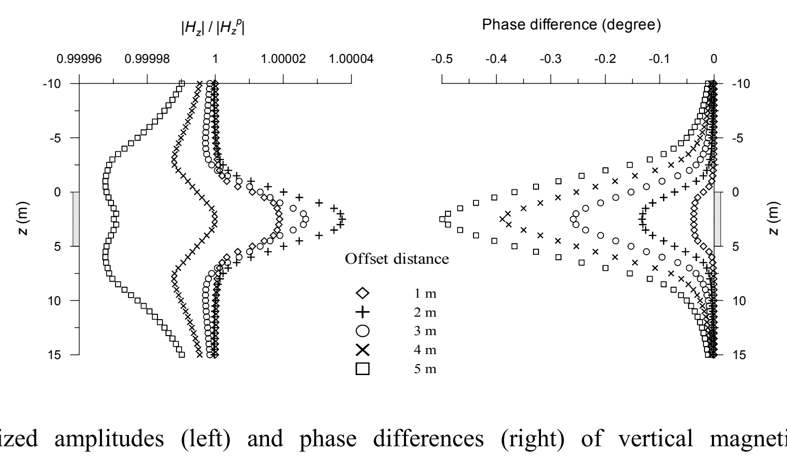

Fig. 2. Normalized amplitudes (left) and phase differences (right) of vertical magnetic fields for the homogeneous casing model shown in Fig. 1 for five source-receiver separations: 1, 2, 3, 4, and 5 m.

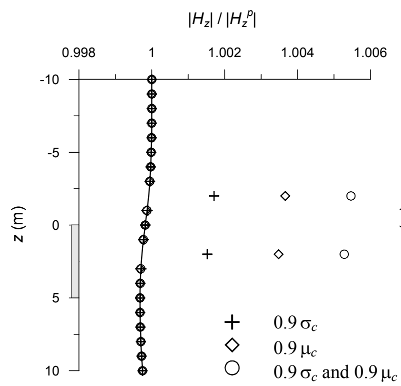

Fig. 3. Normalized amplitudes (left) and phase differences (right) of vertical magnetic fields for a steel casing with a small inhomogeneous part. The inhomogeneous part, 10 cm long and 0.25 cm thick at the outmost part of casing wall, are located at –2 m and 2 m and have 10 % lower conductivity (0.9×10^6 S/m) and/or magnetic permeability ($5.625\mu_0$ H/m) than the surrounding casing wall. A loop current is fixed at –10 m.

plitude response the effect of magnetic permeability variation is larger than that of conductivity variation. In the phase response, however, the effect of magnetic permeability variation is much smaller than that of conductivity variation. In addition, these effects are highly localized. This localization may facilitate processing of EM data.

Also note that the anomaly from the conductive layer can also be recognized in Fig. 3. The anomaly increases as the source-receiver offset is increased, and is much more apparent in phase responses than in amplitude ones. This suggests phase information may be more helpful to pick up the formation resistivity than amplitude information.

EXTRACTION OF FORMATION RESPONSE

To estimate formation response from measurements in a steel casing, it is essential to know how much the electrical property varies inside the steel (Wu and Habashy, 1994). A fluctuation of conductivity and/or magnetic permeability along the casing would pose additional difficulty for data interpretation. To investigate this problem further we introduce a conductivity fluctuation into the uniform casing model shown in Fig. 1. The conductivity variation is assigned in the outermost part of casing wall with 0.25 cm thick and 2 m long, ranging from z = –1 m to +1 m. In this range, the conductivity is made to randomly fluctuate within a 3 % magnitude of the background uniform conductivity of 10^6 S/m.

For a non-uniform casing model with the conductivity variation, we calculate H_z fields with a source-receiver offset of 3 m. The casing non-uniformity significantly affects both amplitude and phase responses as shown in Fig. 4. The responses severely fluctuate over approximately 5 m section ranging from z = –2.5 m to +2.5 m. Although these anomalies are quite large, the magnitude of phase anomalies is relatively smaller than the amplitude ones when comparing with that from the conductive layer. In other words, formation information is more apparent in phase than in amplitude.

The coherent noise event whose dominant spatial frequency is much higher than that of the signal from the conductive layer may be greatly suppressed by low-pass filtering. We applied a Savitzky-Golay filter to removing the high-frequency noise (Press and Teukolsky, 1990). Fig. 5 shows 33-point Savitzky-Golay smoothing filtered phase responses. Although a high-frequency noise still exists in the filtered result, the conductive layer response is successfully recovered from the low-pass filtering. If the signal and noise components of EM fields measured in the cased well have different frequency characteristics, we can design a more accurate filter on this basis.

CONCLUSIONS

We have investigated the effect of non-uniform casing properties on EM fields measured in a steel-cased well embedded in a layered formation, and used a finite-element method to simulate EM fields in a medium of cylindrically symmetric geometry. Although the steel casing greatly affects EM signals

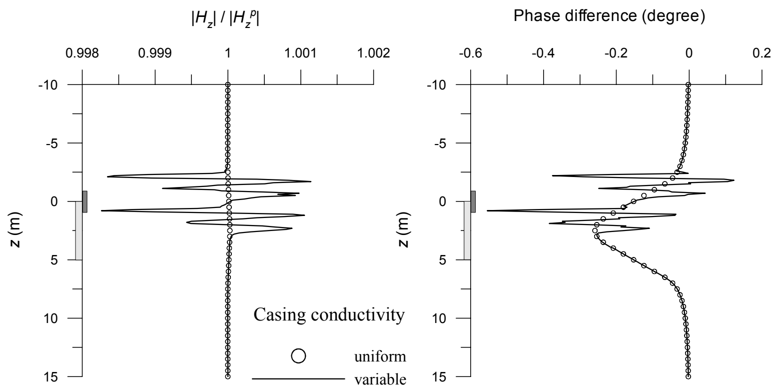

Fig. 4. Normalized amplitudes (left) and phase differences (right) of vertical magnetic fields measured in a cased borehole with variable conductivity, ranging $z = -1$ m to 1 m. The source-receiver separation is 3 m.

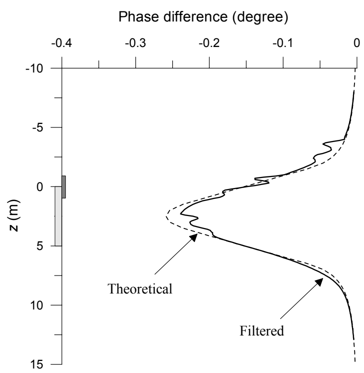

Fig. 5. 33-point Savitzky-Golay smoothing filtered phase responses. Sampling interval is 10 cm.

induced by the layered formation, phase anomalies appear more useful to pick up the formation resistivity than amplitude anomalies. The effect of casing non-uniformity is quite large but highly localized. When the conductivity is rapidly varied in the casing wall, the resulting phase responses also change rapidly. A cross correlation function of these variations has two clear negative peaks with amplitudes less than –0.9, and the distance of the two peaks is identical to the source-receiver separation to represent the localization of casing effect. The coherent noise event, whose dominant frequency is much higher than that of EM signals from the formation conductivity, can be greatly suppressed by low-pass filtering.

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