Study on a Modified Fixed Central-loop TEM System for Deep Sounding

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SUMMARY

The central-loop TEM technology has been widely used in geological exploration. For efficient working, a square (or rectangular) loop is generally used instead of the circular one. One may define a range of one ninth of central part (can be approximately regarded as uniform) as the central survey location, which can be referred as a modified central-loop configuration.

However, the obtained field parameters at such non-central positions usually calculated by the central-loop formula result in decreased accuracy in the explanation. The large-fixed loop has advantage to calculate the induction potential at any point inside or outside the loop. We in this study introduced the formula for the larger-fixed loop into the above modified central-loop system and solve the problem, in which electromagnetic response of any field point has been obtained by using an electric dipole integration method. Both theoretical modeling and real application indicate that such combination not only improves the accuracy for the TEM survey, but also enlarges the exploration depth due to a large loop is used in the deployment.

Introduction

As one of popular system, a central loop configuration (see Figure 1a) TEM sounding is widely used in environmental and groundwater surveys due to its adaptable to working site. The TEM method has many attractive applications in geological surveys and near surface engineering exploration where the buried depth is less than 500 m (i.e., Raiche et al, 1987; Danielsen, 2003; Xue et al., 2004). It is also a favorable choice in hydrogeology exploration of coal mines and in metal mining exploration.

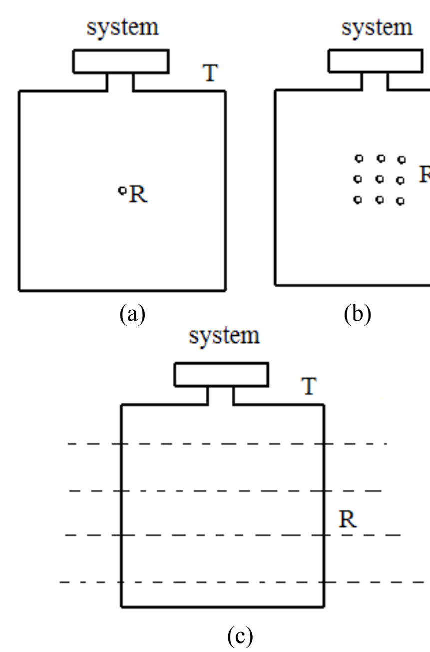

Figure 1 Three different designs for the TEM sounding methods (diagram a: central-loop; diagram b: large-loop source and diagram c: large-fixed loop).

In the TEM depth soundings, because of limited transmitter current intensities, an increase in the depth of investigation can not be achieved by an infinite increasing the loop area. Meanwhile, it is not convenient and also not efficient to move the emitting loop from one place to another so as to observe the central TEM signal, when the side length is large, say, larger than 300 m. To overcome such a problem and also decrease an effect of local lateralheterogeneity, one may observe the TEM values around the central position within a fixed range inside the large loop and deploy an improved central-loop source design (see Figure 1b). It is referred as a modified central-large-loop system. But for this special configuration, the apparent resistivity at every receiving point is usually calculated by the formula of central-loop during the data interpretation. As a result, an extra error will be added to the modified central-large-loop system.

However, it is reasonable to solve the problem with a large-fixed loop (see Figure 1c). The TEM surveys based on the large-fixed loop design is relatively matured technique (i.e., Lee and Lewis, 1974; Asten and Price, 1985).

Actually, for the large square-loop emitter, it really functions a stacked electromagnetic field with many magnetic dipoles located separately along the loop, and its response field may be obtained along the loop with some kinds of numerical integrations. Poddar (1983) and Anderson (1985) drew a frequency-domain electromagnetic field expression by using the reciprocity principle in the electromagnetism and normal dipole-magnet emitted electromagnetic field, in which an inverse Hankel transform of the frequency-domain response of a horizontal electric dipole was integrated around the perimeter of the loop. The result was then transformed into the time domain.

In this study we proposed an idea to calculate the electromagnetic field emitted by the large-loop source using the corresponding expression, previously developed for the EM field emitted by the large-fixed loop source, and hence define a new apparent resistivity and corresponding formula for the central-loop design based on the study of Raiche et al (1987), which improves the accuracy in the data interpretation. Theoretical modeling indicated that it is able to improve the exploration accuracy and enlarge the penetration depth. In the TEM survey with the modified central-loop system for locating water enriched area in the deep buried coal mine in Yangquan region of Shanxi province, China, the interpreted results are tested by the later drillings, which validate our combined method to be a reliable and an efficient method for deep soundings.

2 TEM Formulae for the Central-loop Source and the Large Fixed-loop Source Designs

2.1 The Central-loop Source

The following equations (1-2) and (3-4) provide an initial estimate of the apparent resistivity for the central-loop system in later time and in early time, respectively (Nabighian, 1979),

$$\rho(H_z(t)) = \frac{\mu_0}{\pi t}\left[\frac{\pi I_0 L^2}{30 H_z(t)}\right]^{2/3} \tag{1}$$

$$H_z(t) = \frac{I_0 L^2 \sigma^{3/2} \mu_0{}^{3/2}}{30\pi^{1/2} t^{3/2}} \tag{2}$$

$$\rho(\frac{\partial H_z}{\partial t}) = \frac{L^3}{3\mu_0 I_0}\frac{\partial H_z(t)}{\partial t} \tag{3}$$

$$\rho(H_z) = \frac{L^3}{3\mu_0 I_0} H_z(t) \tag{4}$$

where, σ is conductivity and t is decayed time when the current is powered off and μ_0 is permeability of a free space. I_0 is transmitter current and t is time. H_z is vertical component of the magnetic field.

The converted depth can be calculated by (Spies, 1989),

$$h(\mathrm{t}) = \sqrt{\frac{\rho(t)\times t}{2\mu_0}} \tag{5}$$

2.2 The Large-fixed Loop Source

The diagrammatic explanation of response calculation for the large-fixed loop source design is drawn in Figure 2 and the coordinate of the loop central is (0, 0). The loop dimension are $2a$ and $2b$ in the X and Y directions, respectively. Receiver (x_R, y_R) can be located inside or outside the loop. (x, y) is the position of the dipole, the four sides of the loop are named as A, B, C and D, respectively.

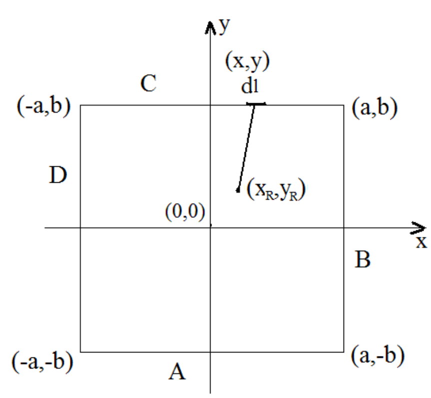

Figure 2 Diagrammatic explanation for calculating the response for the large-fixed loop source.

The total field contribution is the summation over each side,

$$H_z = H_{zA} + H_{zB} + H_{zC} + H_{zD} \qquad (6)$$

where H_{zA}, H_{zB}, H_{zC} and H_{zD} denote the electromagnetic field contributions from sides A, B, C and D, respectively.

In the uniform half space, the vertical component of the magnetic field due to single dipole is (Nabighian, 1979),

$$H_{zdl} = \frac{Idlr}{4\pi r^2}\frac{y}{r}\left[\left(1-\frac{3}{2u^2}\right)\right]erf(u) + \frac{3}{u\sqrt{\pi}}e^{-u^2} \qquad (7)$$

and $u = \sqrt{\mu_0 r^2 / 4\rho t}$,

$$r = \sqrt{(x-x_R)^2 + (y-y_R)^2}$$

where, *erf* (u) is error function ,I denotes transmitter current, dl denotes the length of dipole, r is the distance from transmitter to receiver. From the definition we can write the vertical component of the magnetic field for each side as follow:

$$H_{zA} = (b+y_R)\int_{-a}^{a}\frac{\varphi dx}{r} \ , \qquad (8)$$

$$H_{zB} = (a-x_R)\int_{-b}^{b}\frac{\varphi dy}{r} \ , \qquad (9)$$

$$H_{zC} = (b-y_R)\int_{-a}^{a}\frac{\varphi dx}{r} \ , \qquad (10)$$

$$H_{zD} = (a+x_R)\int_{-b}^{b}\frac{\varphi dy}{r} \ , \qquad (11)$$

where $$\varphi = \frac{I}{4\pi r^2}[(1-\frac{3}{2u^2})erf(u) + \frac{3}{u\sqrt{\pi}}e^{-u^2}]$$

(12)

For layered earth, equation (12) can be written as (Kaufman and Keller, 1981):

$$\varphi = \frac{2}{\pi}\int_0^{\infty}\mathrm{Im}(\frac{I}{2\pi}\int_0^{\infty}\frac{\lambda}{\lambda+u_1/R_1}J_1(\lambda r)d\lambda)\frac{\cos\omega t}{\omega}dt \quad (13)$$

where Im denotes the imagery part and λ is integration variable. $J_1(\lambda r)$ is the Bessel function and ω is circular frequency.

$$R_1 = cht[u_1 h_1 + arcth(u_2 h_2 + ... + arcth\frac{u_{N-1}}{u_N})] \ ,$$

$h_1, h_2, ...h_N$ are the depths of N-layered earth, respectively, and $u_1, u_2, ..., u_N$ can be calculated by the following equations:

$$u_i = \sqrt{\lambda^2 + k_i^2} \ ,$$

$$k_i = -i\omega\sigma_i\mu \ , \ i=1,2,......,\mathrm{N} \qquad (14)$$

For a uniform half space, according to equations (6-13), one can get the vertical magnetic field at any point inside or outside the loop. Similarly for a layered earth, according to equations (6-12) and (14), one can get the vertical magnetic field at any point inside or outside the loop. Once the vertical component of the magnetic field is known, it is easy to obtain the apparent resistivity according to equations (6-14).

3 THE CHARACTERISTIC OF THE FIELD RESPONSE

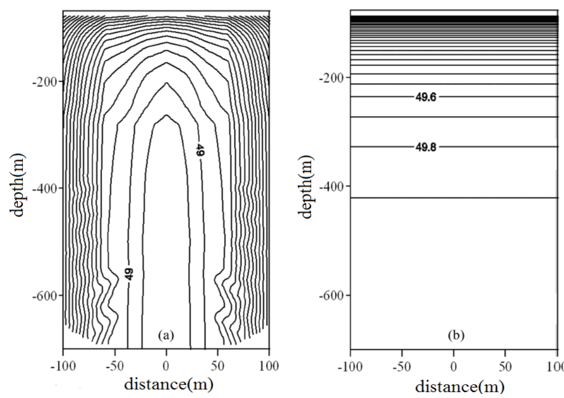

Figure 3 The apparent resistivity profiles obtained by the central-loop (diagram a) and the large-fixed loop source (diagram b).

Let us consider a theoretical case, where the uniform resistivity is 50 Ω m, the emitted loop square is 600 m×600 m, the effective receiving area is 10000 m^2 and the longest observed time is 25 ms. There are in total 40 channels. The apparent resistivity of theoretical simulation results are shown in Figure 3 (diagram a: calculated result by equation 4 and diagram b: calculated result by equations 6-14). From Figure 3a we see that there is a serious distortion (or side effect) at the edge of the observed region. While in the Figure 3b such side effect does not exist. In order to evaluate how lager is the difference between the central position and the edge point with varied distance, Table 1 lists the induction potential differences between the central position and the different non-central positions when time is 3.86 ms, which shows that the longer the distance from the central position, the lager the relative difference.

4 CASE STUDY

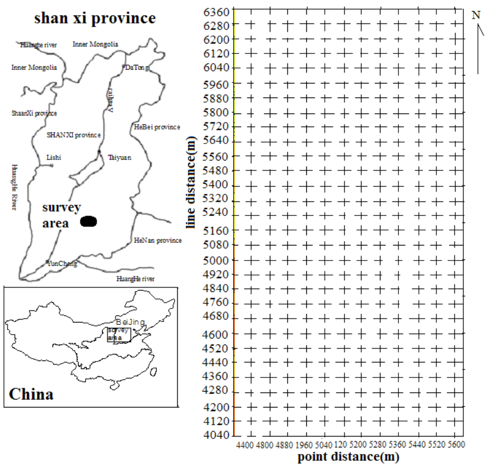

Figure 4 Sketched map showing study regions

The water enriched area in coal stratum is one potential danger to the mine production safety. Therefore, it is necessary to detect water enriched body so as to efficiently guide and control coal mining process. Note that the TEM method is sensitive to low resistivity body, and its vertical- and lateral-resolution are high and exploration depth is large, hence, this method were carried out in several active mining regions in north China during the period of 2005–2010 to explore for the hidden extensions of coal mine-out bodies and to search for water enriched area. This paper presents a case studies from north China (Figure 4).

We were invited to conduct the TEM survey in that region. The primary purposes are to outline the water enriched area in the coal stratum, and also the water enriched area underlying the Ordovician stratum. The resistivity of the sandstone, mudstone and coal stratum ranges from 40 Ω m to 340 Ωm. Limestone has a relative high resistivity. Because the non-uniform distribution of the water enriched component between the top and bottom of the coal stratum and the existed cracks and faults, the electrical property changes quickly, resulting in a low resistive belt (or area) against the surrounding rock. This is the foundation to use the TEM to locate the water enriched area in the coal stratum. We exploited the large-loop source design according to real geological setting. The side length of the emitting loop is 600 m and we observed the derivative of magnetic component (dB/dt) values inside the loop.

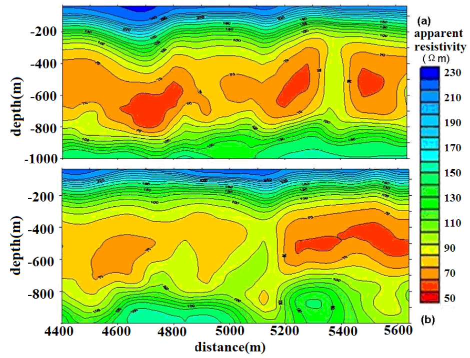

Figure 5Two different apparent resistivity profiles obtained by the large-fixed loop source design (diagram a) and by the central-loop source design (diagram b).

The Canadian made V-8 electrical instrument was used. The switch off time is 0.05 ms, the input voltage is 12-108 V, the output current is 40 A and the output power is 2.8 KW. The probe type is SB-18K (p) whose frequency is 18KHz ±10%. The size of the probe is 60 mm in radius and 615 mm in length, and its effective area is 10000 m^2 . The probe has a sensitive larger than 40 µv/nT. Hz (less than 10 KHz frequency band). It has a low noise level, high sensitivity and linear response. Meanwhile, it is easy to use.

Figure 5a is the apparent resistive profile calculated by the formula of the large-fixed loop source design (equations 6-14) and while Figure 5b is the corresponding profile obtained by the formula of the central-loop source design (equation 4) along the line 5320. The depth conversion was conducted by the formula (4), which was cross checked with the later drilling data. It is obvious that the contour map obtained by the formula of the large-fixed loop source is smoothly varied and there is no side effect in general.

Fig.6 is two horizontal slices of the apparent resistivity corresponding to the altitude 540m and 430m. In this figure the apparent resistivity varies from 50 Ω m to 230 Ω m. The distribution of the apparent resistivity has low values in the southern part than in the northern part. There exists a relatively larger low anomalous resistivity area in the southern part of the survey region, which may be inferred as the water enriched area.

If 65 Ω m is used as the threshold for locating the water enriched area, in the upper map, we may determine 6 such water enriched areas in the coal stratum, which were mainly distributed in the middle and the southern parts of the survey region. In the lower map, there are in total 7 water enriched areas existed.

Such evidences may relate to the local structure and the corrosion phenomena due to the watery constitution. Later drilling verified our interpretation.

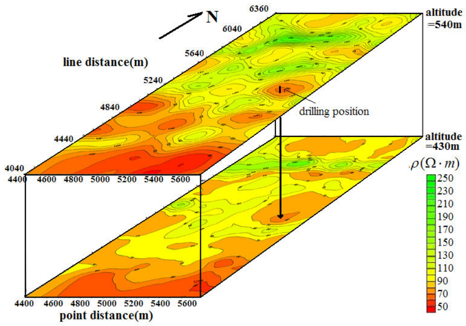

Figure6 horizontal slice of the apparent resistive contour map corresponding to the altitude of 540m and 430m water enriched areas can be located if the resistive threshold is less than 65 Ω m.

5 CONCLUSIONS

The central-loop source design is simple in terms of calculation, but it has low working efficiency; while the large-fixed loop source design has high working efficiency, but has relatively low field values outside the loop, which may influences the interpreted results. In order to reduce the local lateral heterogeneity in electrical property, one in general observes a number of receiver points around the central position of the loop, and forms the larger-loop source design, which we referred it as a modified-central loop design of the TEM survey. The modified central-loop design of the TEM has high working efficiency and is currently widely used in the engineering investigation and near surface geophysical exploration, but there exists a side effect on the non-central position, because such non-central position is calculated by the formula related to the central-loop source design, which may reduce the interpreted results if the local lateral heterogamous is obvious presented. Therefore, it is suggested that one has to use the formula of the large-fixed loop source design to calculate the apparent resistivity on such non-central positions and hence remove the side effect. The key issue in this paper is to introduce the formula of the large-fixed loop source into the modified large-central-loop source design, which has been tested by both the theoretical simulation and real application to locate the water enriched areas in the coal stratum, and hence improve the accuracy of the interpretation results. Other benefit of doing so is that we enlarge the general exploration depth from 300 m-500 m to 800m-1000m, due to relatively large loop employed. In addition, by using a magnetic probe with large receiving area, we can obtain high quality and smooth data, which needs no further smoothing or filtering.

Acknowledgement

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