Inversion interpretation of CSAMT single-component data

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***Abstract*—CSAMT always use MT to calculate the Cagniard resistivity which is the ratio of electric field component and magnetic field component. CSAMT field source is known and the electric field component and the magnetic field component have a certain relationship with the underground resistivity. Therefore the single-component date including magnetic field component or electric field component can be used to extract the apparent resistivity. In order to improve the influence of noise to data interpretation, the paper put forward that the single-component of CSAMT is used to calculate the apparent resistivity through analyzing the data quality of magnetic field component and electric field component. The generalized inverse matrix inversion method is used and the layer number equals to time channel. The method overcomes the problem that the layer number is low, and the fitting inversion of the apparent resistivity curve in the whole field is realized. The detection of the result of seeper mine-out area in Datong show that the single-component detection and interpretation method is effective.**

Keywords—CSAMT; inversion interpretation; single-component date

I. Introduction

Controlled Source Audio-frequency Magnetotellurics (CSAMT for short) has been applied in geological survey, metal minerals, geothermal, hydro-geology, environmental geology, coal geology and other exploration . The ratio of the electric field component and the magnetic field component is used to define the apparent resistivity of the CSAMT. Although the ratio of apparent resistivity may be offset by the same interference, it is likely that quality of the measured magnetic field and electric field are different and the interference effects are also different because the polarization direction of electromagnetic interference is different, the environment and geological conditions are different (such as the earth's electric field component can't be observed or the quality is not high). However, CSAMT emission current is known, and the single component electric field and magnetic field can be separated so that the interaction between the single component and the magnetic field is avoided.

The single-component apparent resistivity of CSAMT is derived through uniform earth far zone. In order to get the apparent resistivity that has hierarchical capabilities and is whole region, iterative algorithm is widely used [1]. The paper studies on response characteristic of electromagnetic field from theoretical analysis, numerical simulation, data processing and interpretation. Therefore the CSAMT measured data of Shanxi in complicated conditions is processed basing on apparent resistivity formula for accurate response of dipole source electric field. The reliability of ratio apparent resistivity can't be guaranteed because of the near filed effect. Therefore, the curve fitting inversion method overcomes the problem that the layer number is low. The detection of the result of seeper mine-out area in Datong show that the single-component detection and interpretation method is effective

II. The Single-Component response Analysis of CSAMT

Generally, the field source of CSAMT exploration application is the grounding electrical dipole source. In general case, the displacement current is much less than the conduction current in the frequency range of CSAMT（0.1 Hz < f < 10 5Hz）. Under quasi-static condition, every component analytic expression of the horizontal layered homogeneous conductive earth surface, the electric dipole source, the electric and magnetic field in whole region is

$$E_x=\frac{\mathrm{i}\omega\mu_0 Il}{4\pi}\left\{\int_0^\infty\left[\left(\frac{1}{K_0+K_1G_k}-\frac{1}{\xi_0+\xi_1G_\xi}\right)-\cos2\theta\left(\frac{1}{K_0+K_1G_k}+\frac{1}{\xi_0+\xi_1G_\xi}\right)\right]\lambda\mathrm{J}_0(\lambda r)\mathrm{d}\lambda+\cos2\theta\int_0^\infty\left(\frac{1}{K_0+K_1G_k}+\frac{1}{\xi_0+\xi_1G_\xi}\right)\frac{2}{r}\mathrm{J}_1(\lambda r)\mathrm{d}\lambda\right\} \quad (1a)$$

$$H_y=\frac{Il}{4\pi}\left\{\int_0^\infty\left[\left(\frac{K_0}{K_0+K_1G_k}+\frac{\xi_0}{\xi_0+\xi_1G_\xi}\right)-\cos2\theta\left(\frac{K_0}{K_0+K_1G_k}-\frac{\xi_0}{\xi_0+\xi_1G_\xi}\right)\right]\lambda\mathrm{J}_0(\lambda r)\mathrm{d}\lambda+\cos2\theta\int_0^\infty\left(\frac{K_0}{K_0+K_1G_k}-\frac{\xi_0}{\xi_0+\xi_1G_\xi}\right)\frac{2}{r}\mathrm{J}_1(\lambda r)\mathrm{d}\lambda\right\} \quad (1b)$$

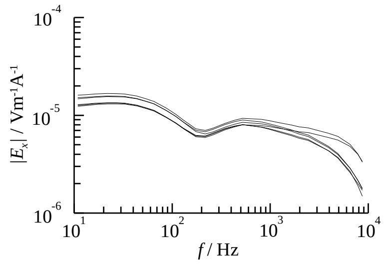
The calculating formula of ratio apparent resistivity is

$$\rho_\omega^{E_x/H_y}=\frac{1}{\omega\mu}\left|\frac{E_x}{H_y}\right|^2. \quad (2)$$

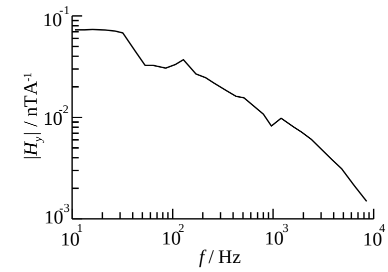
When Ex and Hy are disturbed, causing the same distortion, the interference can be offset using the formula (2) so as to contain the anti-interference ability to a certain degree. However, it is rare that offsetting interference and obtaining high quality data precisely in exploration. It is more common that the components of the electric field or the magnetic field show different characters in various kinds of disturbances.

Fig. 1 is the measured curve of CSAMT in a mining area of Datong, Shanxi. And the electric field Ex component of the 6 measurement positions has not apparent disturbance (Fig. 1a). However, the ratio of the measured point to the apparent resistivity value has a more severe distortion (Fig. 1c) because of 1 measured point on the Hy noise (Fig. 1b). In addition, the 2kHz~10kHz electric field Ex in Figure 1a reflects the smooth fluctuation of the geological condition, and the response frequency band in Figure 1c shows a similar distortion after the amplification of the ratio apparent resistivity. To make use of the different character of each component in the interference performance, the CSAMT exploration can be expanded, may also seek to eliminate the interference of the new way.

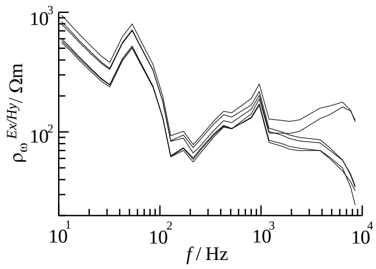
When the electric field and the magnetic field measurement are arranged across faults, the apparent resistivity obtained by the ratio method may also cause the false formation. In addition, the various components of the electromagnetic field in the terrain, surface electrical and other conditions are different, so as aspects of the field division, recording points, etc. So electric or magnetic field separated from CSAMT can exploit data when the observation quality is not high, can also provide the CSAMT with diversified exploration and data processing interpretation methods together with the ratio of apparent resistivity.



(a) electric field $|E_{x|}$ curve



(b) magnetic field $|H_y|$



(c) Curve ratio apparent resistivity curve

Fig. 1 CSAMT observation data in Datong Coal Mine, Shanxi Province

III.THE SINGLE-COMPONENT APPARENT RESISTIVITY CURVE FITTING INVERSION ALGORITHM OF CSAMT IN FULL FIELD AREA

In the MT method, the current intensity of natural field source can't be learned and the absolute value of apparent resistivity can't be determined. The apparent resistivity is defined by the plane electromagnetic wave impedance just as in equation (2) comparing with homologous electric and magnetic fields. The CSAMT source (current) is known and controlled, and the apparent resistivity of the single component can be defined. In the frequency sounding method of parallel development with CSAMT, the formation factor $G_k = G_\xi = 1$ generally is taken far field asymptotic in the region's formula (1), namely each component of apparent resistivity formula t are derived when the product of uniform earth wavenumbers k_1 and distance r of send and receive from $|k_1 r| >> 1$,

$$\rho_\omega^{E_x} = \frac{4\pi r^3}{Il}\left|\frac{E_x}{3\cos 2\theta - 1}\right| \quad (3a)$$

$$\rho_\omega^{E_y} = \frac{4\pi r^3}{3Il}\left|\frac{E_y}{\sin 2\theta}\right| \quad (3b)$$

$$\rho_\omega^{E_z} = \frac{4\pi^2 r^4}{\omega\mu_0 (Il)^2}\left|\frac{E_z}{\cos\theta}\right|^2 \quad (3c)$$

$$\rho_\omega^{H_x} = \frac{16\pi^2 r^6 \omega\mu_0}{9(Il)^2}\left|\frac{H_x}{\sin 2\theta}\right|^2 \quad (3d)$$

$$\rho_\omega^{H_y} = \frac{16\pi^2 r^6 \omega\mu_0}{(Il)^2}\left|\frac{H_y}{3\cos 2\theta - 1}\right|^2 \quad (3e)$$

$$\rho_\omega^{H_z} = \frac{2\pi r^4 \omega\mu_0}{3Il}\left|\frac{H_z}{\sin\theta}\right| \quad (3f)$$

In the initial parameters setting of the curve fitting inversion:The asymptotic value is set for the subsurface resistivity value because of the far zone apparent resistivity indicates the true earth resistivity when the apparent resistivity curve appears first asymptote. The near field apparent resistivity is 1/2 of uniform earth resistivity. So the asymptotic value multiplied by 2 for the bottom of the resistivity values when the apparent resistivity curve gradually appears tail line.

The number of layers has a decisive influence on the fitting results. When the number of layers is consistent with the actual formation, the fitting results are close to the true formation. If the number of layers is more than the actual formation, the inversion can be returned to the actual number of layers. If the actual number is less than the actual number of layers, it will not be automatically increased, so it can increase the number of layers basing on geological data.

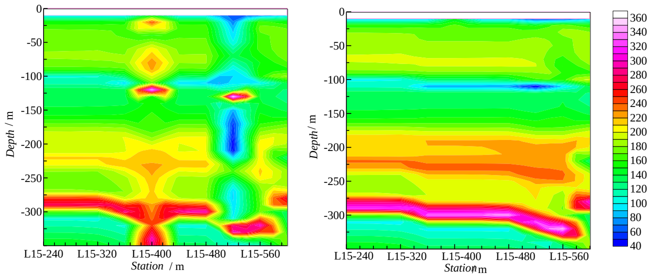
According to the improved generalized inverse matrix inversion theory, the formation layers can be the same as the number of frequency points. In practical exploration projects, electrical logging reveals that the electrical layer is usually more than dozens of layers. By using the frequency points as the number of layers, the inversion results can not only maximize the inversion results, but also enable the resistivity depth profiles to be more precise in the formation of electrical properties

IV. THE INVERSION OF CSAMT MEASURED DATA

In CSAMT detection of 2#, 4#, 14# water-filled goaf in Datong coal mine area, the maximum detection depth is 350 m according to the depth of coal seam, and according to the far field conditions and signal to noise ratio, the distance of sending and receiving is 3000 m ~ 3500 m, the point spacing is 20 m and the working frequency is 10.67 Hz ~ 8533 Hz were, observing 31 frequency totally. In the area, there are the distribution of surface loess, sub-clay, sub-sand, sand, gravel and gravel, and the measured

TABLE I. AVERAGE RESISTIVITY AND BED THICKNESS OF 315 MINING AREA OF YANZISHAN COAL MINE OF COAL FIELD, SHANXI PROVINCE

stratum **System**	**series/formation**	**lithology**	**resistivity** $\rho/\Omega.m$	**control parameter**	**thickness** *h*/m	**control parameter**	**depth** *H*/m	**sequence**
quaternary	holocene series	loess、loam	30	1	3	1	3	1
	upper pleistocene	loam、gravel	60	1	5	1	8	2
tertiary	pliocene	sandy clay	100	1	5	1	13	3
cretaceous		sandy conglomerate	120	1	15	1	28	4
		sandy mudstone	100	1	25	1	53	5
		sandy conglomerate	170	1	15	1	68	6
				1	15	1	83	7
jurassic	Yungang formation	sandy mudstone	120	1	12	1	95	8
		sandy conglomerate	150	1	5	1	100	9
	Datong formation	coal2#	280	1	1.5	1	101.5	10
		siltstone	100	1	10	1	111.5	11
				1	15	1	126.5	12
				1	25	1	151.5	13
		sandstone	160	1	15	1	166.5	14
				1	20	1	186.5	15
		sandy mudstone	135	1	15	1	201.5	16
		coal4#	300	1	1	1	202.5	17
		sandstone	180	1	5	1	207.5	18
				1	15	1	222.5	19
				1	20	1	242.5	20
		sandy mudstone	150	1	20	1	262.5	21
		coal8#	260	1	0.5	1	263	22
		sandy mudstone	100	1	20	1	283	23
		coal14#	380	1	4	1	287	24
		gritstone	270	1	3	1	290	25
		sandy conglomerate	300	1	5	1	295	26
	Yongdingzhuang formation	siltstone	100	1	10	1	305	27
		medium sandstone	260	1	10	1	315	28
Final hole (the resistivity and thickness of this section is estimated)			350	1	15	1	330	29
				1	20	1	350	30
				1				31



(a) (b)

Fig. 2 Resistivity-depth section along L15 Line of CSAMT exploration for Mining Area(a) electric field amplitude curve fitting inversion (Iterative 10 times, the fitting difference: the measuring point 400 and 520 for 6.72% and 9.17%, and the rest of the measuring point 2.93%~4.26%); (b) Electric field phase curve fitting inversion (iteration 10 times, fitting difference: 2.68%~3.98%)

electric field curves have the translation caused by uneven surface electrical properties, as shown in Figure 2. But the topography in the area is relatively flat, and the formation is relatively stable, so the generalized inverse matrix inversion can be used in. Table 1 is the average resistivity and layer thickness of the region, which is the initial parameter of inversion.

Fig. 2a is the resistivity-depth profile of the L15 line electric field amplitude curve fitting inversion. The curves shift causes the beadlike high and low resistivity in L15-400, L15-520 points and the nearby. The longitudinal electrical properties of the deep strata are usually not represented by the curve shift. Drilling, geological and mining data show that measured fault zone seems to be no graben, no more than 5 m and the collapse column is the coal 14#. Therefore, the obtained resistivity depth profiles are shown in Figure 2b on phase curve of electric field of inverse fitting. Phase inversion has a clear layered formation, which is consistent with the general situation of the area structure. On the basis of geological and mining records, 100 m left and right depth of the thin low resistivity layer is inferred to be 2# coal water goaf, which L15-360 ~L15-560 is rich area and L15-500 ~L15- 540 is strong rich water district. There is no obvious low resistivity anomaly in 200 m of depth4# coal occurrence and there is no water inference. The second highest resistance of L15-225 ~L15- 250 range is inferred to coal 8# which can't be produced; After the exploration, the water quantity of L15-520 point water discharge hole confirms the inference of 2# coal and 14# coal water.

V.CONCLUSIONS

The sensitivity of electric field and magnetic field to interference is different, and the single component of electric field and magnetic field is separated from the apparent resistivity ratio to cope with different interference environments. The objective of studying the whole region apparent resistivity algorithm is that overcoming the limitation of the apparent resistivity in the far area, and obtaining the ability of stratification. The quantitative inversion of curve fitting has such a function. Therefore, the quantitative inversion fitting is a way to get close to the true resistivity when the measured area is stable and the dip angle is not more than 5. In quantitative retrieval of the initial value set, the apparent resistivity debut and tail asymptotic line can provide more accurate surface resistivity value parameter and the general underlying resistivity values. With the layer number setting of the real stratum, the layer thickness section has a more precise expression. CSAMT detection of the water collecting area in Shanxi proved that the single component detection and interpretation method are effective.

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