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The Effect and Application of Single Components in CSAMT

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Abstract: As the Controlled Source Audio Frequency Magnetotelluric method (CSAMT) was developed on the basis of MT, its methodologies, data processing and interpretation also follow the MT method techniques. Under normal circumstances, the Cagniard resistivity parameters which were defined in the MT method could be used to finish data interpretation. However, on using the Cagniard resistivity parameters several problems will be faced. These are topographic effects, static effects, strong human noise interference and some complex environment noise. Making full use of all information of various components in the scalar observation are the only way to solve the problem. In this study, the theoretical analysis, numerical calculation and data processing and interpretation are combined. This combination is used to study a single-component characteristics of electromagnetic response in the magnetic field and the electric field. It is found that the magnetic field component is less sensitive to the impact of topography. So, the magnetic field component can be used as a reference for topographic correction in the case of undulating topography so as to obtain more objective results of data processing and interpretation. On the other hand, the electric field component is more sensitive to the geoelectric structure, so, it is still possible to complete the task of geology by using single electric field component for data interpretation in the strong electromagnetic interference region ,where the magnetic field was badly interfered. In this paper, an exact expression of electric field apparent resistivity with electric dipole source is used to calculate the CSAMT data. This data is collected from an ore mine with complex topography in Shanxi Province, China another data is collected from an urban district in Tangshan, Hebei Province, China. where the data was seriously interfered by human noise. A good results were obtained from these applications.

Key words: CSAMT; Electric Field Component; Magnetic Field Component; Topographic Effect; Electromagnetic Interference.

INTRODUCTION

Controlled Source Audio Frequency Magnetotelluric method (CSAMT) is one of the electromagnetic exploration techniques developed in 80s in the 20th century (Goldstein, M.A., and Strangway, D.W., 1975, Zong, K.L., *et al*., 1986). Both theory and instrument are constantly developed and perfected. Zong, K.L. *et al*. (1991) established the methodology and application of CSAMT. After nearly 20-years, development of the theoretical method, forward modeling, data processing and interpretation of such subject have gained a great deal of research results in this technical field, Bartel, L.C., and Jacobson., R.D., 1987 Boschetto, N.B. and Hohmann, G.W., 1991 Chen, M.S., and Yan, S., 2005 Dey, A., and Morrison, H.F., 1979 He, J.S., 1990, Kuznetzov, A.N., 1982 Lu, X., Unsworth, M., and Booker, J., 1999 Mitsuhata, Y., 2000 Routh, P.S., and Oldenburg, D.W., 1999 Sasaki, Y., Yoneda, Y., and Matsuo, K., 1992, Smith, J.T., and Booker, J.R., 1991 Wang, R., Wang, M.Y. and Di, Q.Y., 2006).

This method recently received increased attention for being successfully used as a tool in ore metal mining, petroleum, geothermal resources, underground water, sea-dip and environment exploration, (Wannamaker, P., 1997, Ward, S.H., 1971, Yamashita, M., Hollof, P.G. and Pelton, W.H., 1985). In groundwater resource exploration and geothermal exploration, a remarkable results were achieved by finding fault-type storage structure and carrying out CSAMT survey against the feature of montane karst fissure water (Bartel, L.C., and Jacobson., R.D., 1987). CSAMT is also a good means in searching structures contain-ore and an abnormal

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body's shape and position (Boschetto, N.B. and Hohmann, G.W., 1991). In the prediction of mining geology faults and karst cave provide an important basis for prevention and control disasters by detecting the distribution of water-bearing zone of roof and floor of the ore (Chen, M.S. and Yan, S., 2005).

CSAMT is a method that uses far-zone measurement and calculates the ratio of the two $Z_{xy} = \frac{E_x}{H_y}$ (known as impedance) by measuring a set of mutually orthogonal electric, magnetic field component to obtain the subsurface apparent resistivity distribution.

The CSAMT method adopts the ratio of apparent resistivity similar to the MT, hence the accuracy of apparent resistivity depends on the accuracy of the two components Ex and Hy. However, CSAMT does not exactly similar to MT, it has its own characteristics, especially, in the case of mountain environment with very severe topographic effects, and some complex environments with relatively serious static effect. In addition, the electromagnetic field signal is originally weak in urban environment, once the work area is largely disturbed, Ex and Hy components would be inevitably impacted in different degrees. Therefore, it is not wise to completely adopt the data processing and interpretation methods of MT, which is applied to larger structure exploration, especially in the case of the higher accuracy requirement, and it is necessary to study the different reflection of different components to these effects .Then, eliminate them effectively. In this case, how to reduce interference and to seek more accurate apparent resistivity is very important. Through study of characteristics of CSAMT method is of theoretical and practical significance to develop the method itself.

In this paper, the writers combined theoretical analysis, numerical calculation and data processing and interpretation to study the single-component characteristics of electromagnetic response in magnetic field and electric field. Exact expression of electric field apparent resistivity with electric dipole source is used to calculate the CSAMT data of a mine with complex topography in Datong City, Shanxi Province and the CSAMT data ,seriously interfered by human noise in Tangshan, and in which a good results were achieved.

2- Single-component Theoretical Analysis of CSAMT:

2.1 Calculation Formula:

In the CSAMT method, the apparent resistivity is defined by the wave impedance on the uniform earth surface as follows (Zong K.L., *et al.* 1986)

$$Z_{TM} = Z_{TE} = E_x / H_y = E_y / H_y \tag{1}$$

Where, subscript TM is horizontal magnetic wave, TE is horizontal electric wave, the ratio apparent resistivity (or called the Cagniard apparent resistivity) is derived from the following Formula:

$$\rho_a = \frac{1}{\omega\mu}\left|E_x / H_y\right|^2 = \frac{1}{\omega\mu}\left|E_y / H_x\right|^2 \tag{2}$$

Where, ω, μ are circular frequency and magnetic permeability respectively.

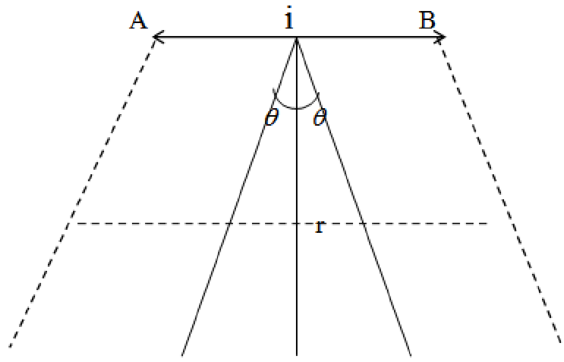


Fig. 1: CSAMT schematic diagram.

At far zone, by the formula of single-component magnetic field Hy and electric field Ex, (Zong, K.L., *et al*. (1991).

$$E_x = \frac{Il}{4\pi\sigma_1}\frac{1}{r^3}\left(3\cos 2\theta - 1\right) \tag{3}$$

$$E_y = \frac{3Il}{4\pi\sigma_1}\frac{1}{r^3}\sin 2\theta \tag{4}$$

$$E_z = (i-1)\frac{Il}{2\pi}\sqrt{\frac{\mu_0\omega}{2\sigma_1}}\frac{1}{r^2}\cos\theta \tag{5}$$

$$H_x = -(1+i)\frac{3Il}{4\pi}\frac{1}{\sqrt{2\mu_0\omega\sigma_1}}\frac{1}{r^2}\sin 2\theta \tag{6}$$

$$H_y = (1+i)\frac{Il}{4\pi}\frac{1}{\sqrt{2\mu_0\omega\sigma_1}}\frac{1}{r^3}\left(3\cos 2\theta - 1\right) \tag{7}$$

$$H_z = \frac{i3Il}{2\pi}\frac{1}{\mu_0\omega\sigma_1}\frac{1}{r^4}\sin\theta \tag{8}$$

Where, r is the distance between field source and measuring point; I is transmitting current. θ is the angle between r and the transmit electric dipole. Iι is electric dipole moment. σ_1 is the earth resistivity, l is the dipole distance from A and B.

$E_{x,}E_{y,}H_{x,}H_y$ decay with $\frac{1}{r^3}$, $E_{z,}$ decay with $\frac{1}{r^2}$, H_z decay with $\frac{1}{r^4}$, $E_{z,}$ can not be surveyed in field exploration. For each component, $E_{x,}E_{y,}H_z$, have a relation with ρ, on the other hand $H_{x,}H_y$ have a relation with $\rho^{\frac{1}{2}}$.

the single component apparent resistivity is derived:

$$\rho_a^{E_x} = \frac{4\pi r^3}{Ia}\left|\frac{E_x}{3\cos(2\theta)-1}\right| \tag{9}$$

$$\rho_a^{E_y} = \frac{4\pi r^3}{3Ia}\left|\frac{E_y}{\sin 2\theta}\right| \tag{10}$$

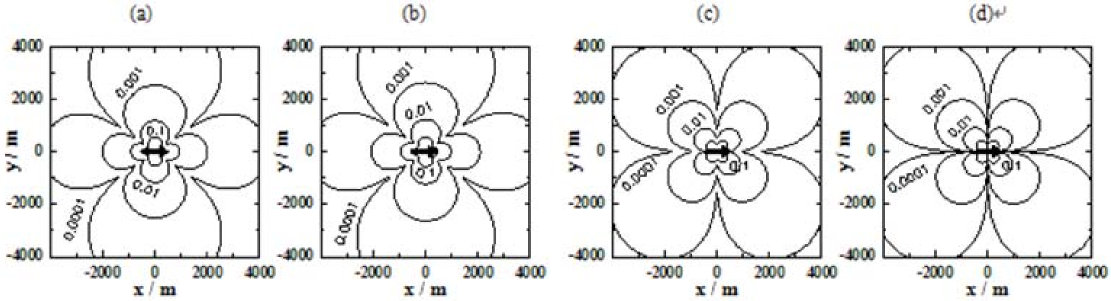
$$\rho_a^{H_y} = \frac{16\pi^2\omega\mu r^6}{9(Ia)^2}\left|\frac{H_y}{3\cos(2\theta)-1}\right| \tag{11}$$

$$\rho_a^{H_y} = \frac{16\pi^2\omega\mu_0 r^6}{I^2a^2}\left|\frac{H_x}{\sin 2\theta}\right| \tag{12}$$

$$\rho_a^{H_z} = \frac{2\pi\omega\mu_0 r^4}{3Ia}\left|\frac{H_z}{\sin\theta}\right| \tag{13}$$

***2.2 The Consistency Between Each Component*:**

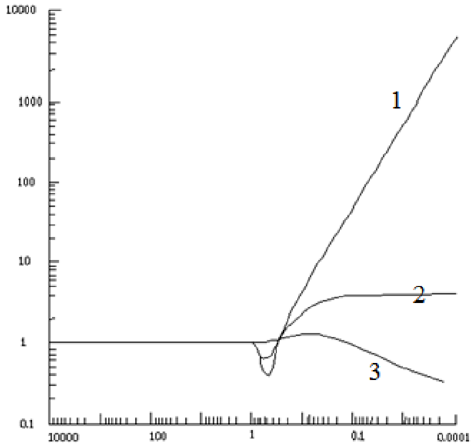
Firstly, each component is calculated on the uniform earth surface and the distribution curve of each component is demonstrated, as shown in Figure 2, (a) is the distribution pattern of electric field | Ex |; (b) is the distribution pattern of magnetic field | Hy |; (c) is the distribution pattern of electric field | Ey |; (d) is the distribution pattern of magnetic field | Hx |. When electric and magnetic component disturb with the same noise, the noise can be removed by equation (2) calculation, but usually, electric and magnetic component disturb with the different noise, it can not removed the disturb by equation (2) calculation. One can get better interpretation result according to the special character of each component. After analyzing this diagram it appears that the distribution of electric field components Ex and Ey are consistent with their corresponding magnetic field components Hy and Hx on the uniform earth surface, the apparent resistivity calculated from Ex / Hy, Ey / Hx has meaningful. However, when distribution pattern of the electric field component Ex and magnetic field component Hx are inconsistent as well as the electric field component Ey component and the magnetic field component Hy, it does not make sense using Ex / Hx, Ey / Hy to define the apparent resistivity.



(f = 2 kHz, r = 500 Wm, electric field unit mV/m,magnetic field unit mA/m)

Fig. 2: Electromagnetic field distribution on the surface of a uniform earth by CSAMT electric dipole electric field $|E_x|$; (b) magnetic field $|H_y|$; (c) electric field $|E_y|$; (d) magnetic field $|H_x|$

The relation of each apparent resistivity is defined by the electric field component the magnetic field component and the ratio method respectively. Then, a designed electrical mode is calculated l ($\rho_1 = 1\Omega \cdot m, \rho_2 = 100\Omega \cdot m$, $h_1 = 1000m, r = 4000m,$) and normalized apparent resistivity curves have been drawn in a same coordinate system, respectively, shown in Figure 3:



$\rho_1 = 1\Omega \cdot m, \rho_2 = 100\Omega \cdot m, h_1 = 1000m, r = 4000m,$

1---- $\rho^{\frac{E_x}{H_y}}$ curve, 2---- ρ^{E_x} curve, 3---- ρ^{H_y} curve

Fig. 3: Graph of theoretical calculation results.

As shown in figure 3, although the middle and tail parts of the $\rho^{\frac{E_x}{H_y}}$ ρ^{E_x} and ρ^{H_y} curves are separate, the front branch of the three curves are basically consistent, which indicates that the apparent resistivity curves individually defined by the three components, all of it can reflect the electrical characteristics of stratum in the far region and can be used in data interpretation.

3. Single Component of CSAMT in Complex Situation:

According to equation (3), it can be seen that, the earth conductivity is linearly related to electric field, while according to equation (4), the earth conductivity and the magnetic field have square-root relation, which indicates that the magnetic field is less sensitive to the changes of electrical parameters of the earth than electric field. The three components Hx, Hy and Ez are less related to the electrical properties of the lower half space, while components Ex,Ey and Hz are close to stratum. Therefore, it is more profitable to measure the latter three components. Thus, if the terrain is rough, the magnetic field parameters can be used as a reference for the topographic correction. i.e., we should make full use of the magnetic field data to do interpretation in the rough terrain work areas.

The Datong coal-field in Shanxi Province has been taken as an example (Fig. 4a). The V8 instrument was used to collect the data, and analyzed the impact of terrain on observational data in mountainous area . Datong Yanzi coal-field is the loess-covered hill knap topography where the underground stratums are flat and stable fig. 4b), but the surface is undergoing erosion and cutting action resulted in uneven electrical effect and brought topography effect.

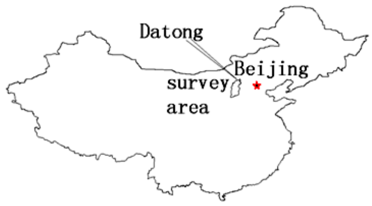


Fig. 4a: Location map of the survey area (Datong coal-field in Shanxi Province).
Left map is China, right map is Shanxi province.

Fig. 4b: The undulating topography in the survey area.

As shown in figure 5, 5a is observational profile curve of the electric field component, 5b is observational profile curve of the magnetic field component, 5c is profile line of terrain. The actual measured electric field Ex, is suffered a lot by the terrain effect. In undulating terrain areas, the electric field curve is distorted in a higher degree, but the magnetic field Hy is not sensitive to the impact of terrain, so, magnetic field curve is a basically straight line and it is only reflects the deep geological structures. Thus it can be drawn that electric field and magnetic field component have different response characteristics to the undulating terrain, and it is necessary to study the single-component apparent resistivity in the case of rough terrain while using CSAMT method.

According to the procedure of measurements, the controlled source audio-magnetotelluric method can be divided into two kinds: CSAMT and CSAET. When applying the CSAMT measurements, you can measure CSAMT magnetic field parameters at the same time when you measure each electric field (Figure 6a), while by the application of the CSAET, you need to measure only one parameter of the magnetic field when measuring electric field (Fig. 6b).

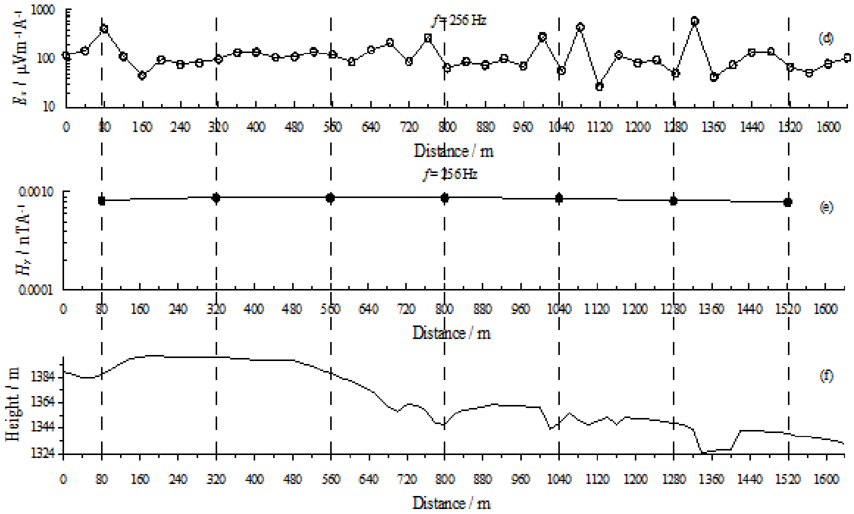


Fig. 5: Observational profile curves of electric field and magnetic field in undulating terrain.

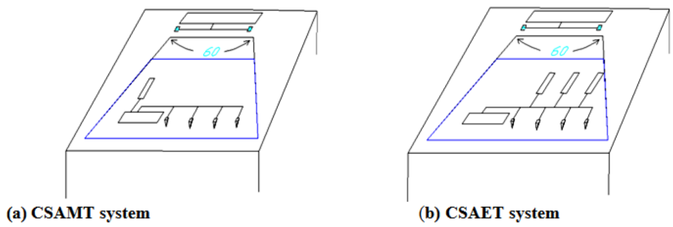


Fig. 6: Comparison chart of CSAMT and CSAET System.

Theoretically, the measuring results of the CSAMT are better than CSAET. However, in order to reduce the workload, CSAMT adopts six electric tracks and one magnetic track for observation and put six electric-track data respectively divide the same one magnetic-track data to calculate the ratio apparent resistivity, and then proceed to data interpretation in most cases, because magnetic field is less sensitive to the change of earth electrical parameters.

Values of each electric track corresponding to each magnetic track should be different, that is mean, each electric field component in different magnetic field should be different. But the biggest drawback of CSAET method is measuring only one magnetic field value, which is clearly inappropriate. Especially, in the situation of poor magnetic field data, one disturbed magnetic field data will affect six values of resistivity. So, using electric field data is particularly important and this would need to make full use of the electric field parameters.

In addition, each component observed in CSEMT mode may have different characteristics when interfered by noise. Generally speaking, electric and magnetic fields measured in an arrangement are interfered by the same noise sources at the same time, so they will have a similar observation data error which can be removed by using the ratio method to calculate apparent resistivity. But the situation is not entirely same, when the electromagnetic interference occurs in a different direction, such as, the electric field in x direction and magnetic field in y direction, thus it will receive different interference: interference of magnetic source and electric source to the magnetic receiver and electric receiver will be different as well; furthermore , connection between magnetic coils, electrodes, layout, and ground may also be different. Therefore, observation quality of electric field and magnetic field will be different.

4. Actual Measurement Data:

The survey area is located in the southern section of central road of Tangshan City, covering an area of about 220,000 m^2. The Tangshan City is located in north of Hebei Province (fig. 7a). The topography of the area is of high land in the north and low land in the south. The northern part is of tectonic erosion hill knap, with an elevation of 50 ~ 530m, undulated topography, strong erosion, and scour development. In the central part the piedmont plain of Yanshan, whose topography is generally flat. The alluvial sloping plain in the southern part is the main physiographic feature in this area, composed of multi-phase alluvial fans coming from Luan River diversion, with an elevation of 5 ~ 50m, flat topography, banks of the rivers that intermittently developed , -level terrace. There were several coal mining subsidence and coal waste piles came into stagnant water pool in eastern and southern urban; dunes distributed along the river in the southeast; erosion residue mound scattered outcropped in urban area. According to the existing coal drilling data: the survey area is composed of the Quaternary (Q), Dyas (P), Carboniferous (C), and Ordovician (O) stratums. Quaternary covers about 30-50 meters, and its propriety is mainly loose sediments, interactively composed of light yellow, light gray sand, gravel and sandy soil and clay layers with different grain size. There were houses and criss-crossed railway in the survey area (fig. 7b).

CSAMT were carried out in the urban area, in which, there are many vehicles, railways, houses, and life or industrial electric power line, these made the survey area badly disturbed and of high electrical noise. Therefore, the measured CSAMT data is not of good quality and it shows distortion in the presented results.

As an example, point 1 of line 3, (Fig. 8) shows the distortion of the electric field component Ex and the magnetic field component Hy.

Figure 8 a, b and c, are the electric field component curves of three adjacent survey points., figure d is the magnetic field curve that shared by the three survey points and figure e is the apparent resistivity curves that calculated by different methods, inwhich the solid line is the apparent resistivity curve calculated by ratio method and the dashed line is the apparent resistivity calculated by electric field component.

It is found that both curves of electric field component Ex and magnetic field component Hy jump and become not smooth, and of weak-signal when curves are subjected to the interference. However, magnetic field component Hy suffered greater impact, whose curve emerged as a serious shock, while electric field curve is relatively smooth. Due to the strong shock of Hy curve, the apparent resistivity calculated by Cagniard formula would be distorted. While the apparent resistivity curve calculated by electric field is relatively good. Therefore, when the ratio apparent resistivity does not meet the requirement, it is feasible to further observe electric field or magnetic field to dig available data.

Fig. 7a: The location map of the survey area (Tangshan city, Yanshan province).
Left map is China, right map is Hebei province.

Fig. 7b: The photo show the urban district in Tangshan, where the data inferred by human noise.

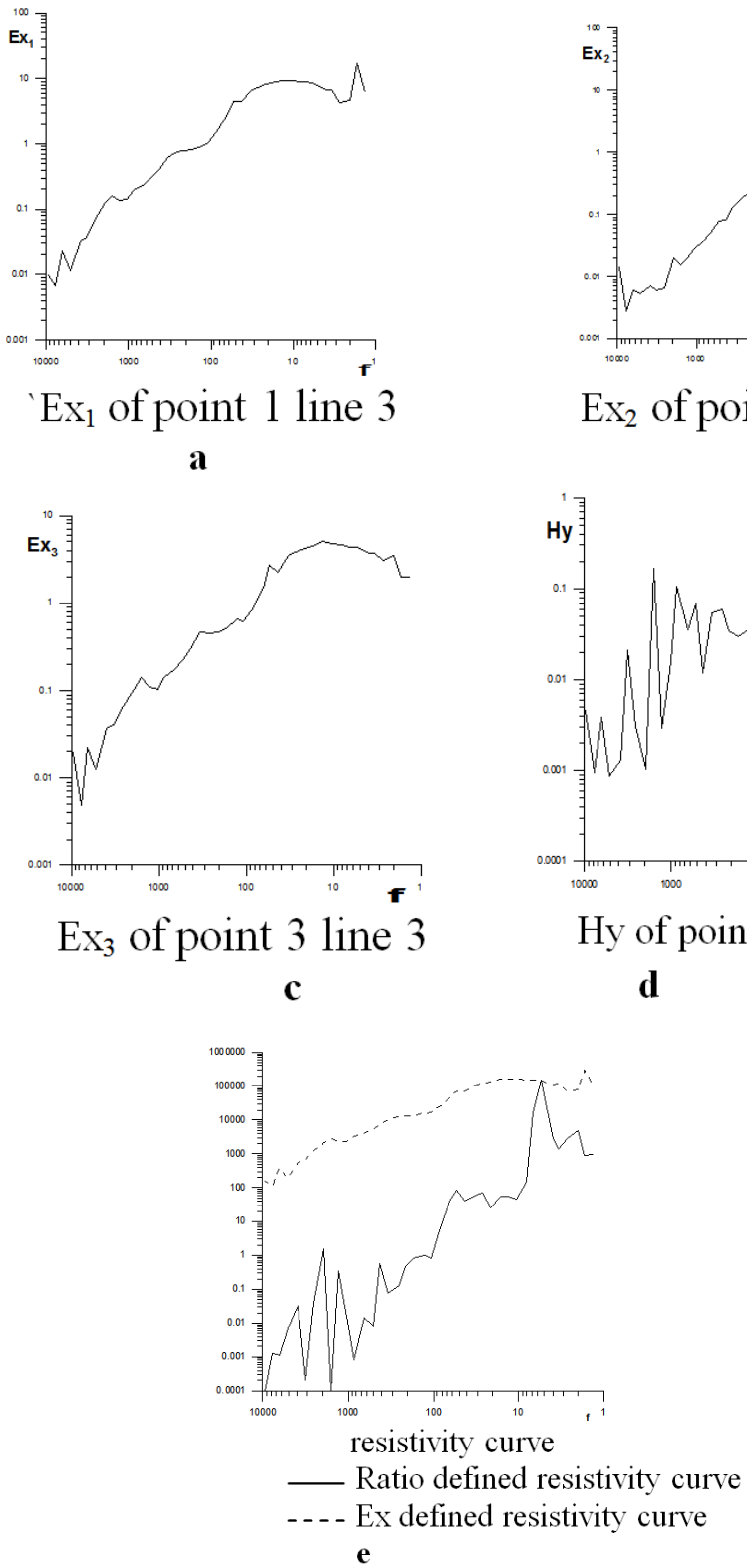


Fig. 8: CSAMT curves of Tangshan urban.

5. Conclusion:

1) Traditionally, the basic data of CSAMT exploration is the ratio of apparent resistivity, and most of the instruments are equipped with the software of this definition. However, interpretation of electromagnetic prospecting is a very complex process analysis, and the actual data proves that the various components of CSAMT have different responses to the lateral changes of electrical properties on the earth surface. Magnetic field component Hy is not sensitive to the lateral changes of electrical properties, but has an equivalent sensitivity to the changes of vertical electrical properties with electric field component Ex. Electric field component is more sensitive to topography and therefore it is feasible to use electric field to do topographic correction.
2) There is no need to do near-field correction and to calculate all-time apparent resistivity for single-component, which will not affect the fitting inversion results but get better stability and convergence of the inversion.
3) Various components of CSAMT have different responses to various interference. In exceptional circumstances, Hy is more seriously subject to electromagnetic interference while Ex is less affected by electromagnetic interference, so, Ex data can be used to ensure the completion of the geological tasks.
4) In CSAMT data processing and interpretation, the use of single-component electric field, magnetic field and ratio apparent resistivity depend on the actual circumstances. Seek for the available information from distortional data and use all the information observed from field synthetically, to obtain a better geological effect and make fine detection possible.

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