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ORIGINAL ARTICLE

Researches on detection of 3-D underground cave based on TEM technique

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Abstract Because of unreasonable coal mining in China, there are many unknown underground caves, and the inhabited environment of humans is threatened by many geologic hazards, such as cracking of the buildings, ground subsidence, etc. To make the coal companies aware of the harmfulness of these hazards, it is urgent to determine the reasons for the hazards. In this paper, transient electromagnetic method (TEM) is used to detect the ground resistance caves, instead of the time-consuming and expensive direct drilling survey. Numerical results of the 3-D synthetic model and real field survey data are given. The results showed that the TEM method can be used to detect a complicated air-filled underground 3-D cave and coincide with the results of direct drilling survey.

Keywords Transient electromagnetic method · Underground cave detection · 3-D modeling

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Introduction

With the rapid economic development in China, there is an enormous need for the detection of underground caves, especially in construction of highways and railways. Generally, the shapes of underground caves are irregular, and to detect them in the complex areas using direct drilling is time-consuming and expensive. The developed gravity (Battaglia et al. 1999) and direct current (DC) geoelectric methods (Mauriello and Patella 2008) can be used to detect underground structures; however, in underground cave surveys, these two methods cannot clearly distinguish the diversified underground caves. Theoretically, the electromagnetic response can reveal the features of different geological structure areas; therefore, it can be used to survey the underground caves in highway and railway constructions. The most successful technique using electromagnetic response for geological survey is the TEM. Compared with traditional drilling survey, the TEM is fast and efficient, and gives a clear image in the detection of a complex geological structure. TEM has been widely used in hydrogeology, oil surface and borehole data studies, and marine investigations (Raiche et al. 1985; Edwards 1997; Taylor et al. 1992; Zhang and Xiao 2001). Therefore, it is not only feasible but also necessary to use TEM for survey of complex underground caves in highway and railway constructions.

Usually, there are two types of underground caves, air-filled and water-filled. The resistivity of a water-filled cave depends on the resistivity of the water, and may be more or less conductive than host rock. In this case, the target body is conductive and it is relatively easy to be targeted by TEM. For air-caves, the target has greater resistance than the surrounding rocks. It is comparatively difficult to use most geo-electrical or electromagnetism (EM) methods to detect this kind of target with high resolution. Up to now, the experimental researches on electromagnetic response of the underground three dimensional (3-D) air-filled caves were scarcely reported, so it is necessary to simulate an air-filled cave based on 3-D models. However, because of the complexity of the geological structures of the 3-D underground air-filled caves, using finite element or finite difference methods to simulate the electromagnetic response suffered from the computer limitation and numerous grids (Wang and Hohmann 1993). Therefore, integral function approach, which needs less memory, has been developed. Simulating 3-D electromagnetic responses were first introduced by Raiche (1974), Weidelt (1975) and Hohmann (1975). Newman et al. (1986) obtained the solution in frequency domain using a discrete convolution technique. Gunderson et al. (1986) computed the electromagnetic response of prisms in two-layer earth; Sanficipo and Hohmann (1985) solved the problem of conductive half-space; and Xiong (1992) studied the electromagnetic response of a 3-D structure. Although the TEM was widely applied in underground cave investigation (Xue et al. 2004; Chen et al. 1995; Zhu and Zhang 2008), there are still few reports on systematic study of underground cave response in the engineering practice of geological exploration.

A method for simulating the electromagnetic response of a 3-D cavity model was developed in this paper, and the 3-D simulating results for resistance caves by using integral function method were given. The simulating results of an air-filled cave with different buried depth and width measure loops are given. At the same time, the experiment of a field exploration for an underground air-filled cave is carried out. The experimental results agree well with the drilling data, and show that TEM can be used to survey the resistant cave as well as the conductivity body. In the completed experiment, the large loop for transmitting and receiving is adopted, which is fast to carry out 3-D cavity configuration. The method has better lateral and vertical resolution of underground target and is less interfered by the inhomogeneity near the surface.

Numerical simulation and analysis

The integral function method is an efficient approach to model TEM response of a 3-D body. Assume that there is a 3-D body in half-space as shown in Fig. 1, a circle loop with the radius of $R$is laid on the ground surface, and the zero point of the coordinate is in the center of the loop, where z presents vertical direction and x, y present horizontal directions, the σ^* is the conductivity of the 3-D body, and σ is the conductivity of the half-space.

The total electromagnetic field component can be written as (Hohmann 1983)

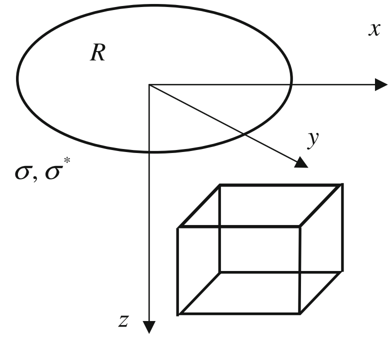

Fig. 1 Survey system of 3-D cave based on TEM

$$H = H_p + H_s \tag{1}$$

where the H is the total magnetic intensity (Wb/m^2), H_p is the magnetic field response without 3-D geological body, and the H_s is the response of the 3-D body. The H_p can be obtained using 1-D forward calculation, or using digital filter method (Kaufman and Keller 1983). According to the law of Green Function, Eq. 1 can be expressed as

$$H = H_p + (\sigma^* - \sigma) \int_{(V)} G^H(r, r')E(r')dv' \tag{2}$$

where r' is the distance between field point to the 3-D body, G^H is the magnetic-type Green Function, and $E(r')$ is electric field intensity inside the 3-D body. Eq. 2 is the basic formula for calculating the TEM response of a 3-D body. To calculate TEM response of a 3-D geological body, the solution of Green function can be obtained in advance from Raiche (1974). Through construction of a set of linear equations, the solution of Eq. 2 is obtained, and then, the results were transformed into time domain. Magnetic intensity can be calculated according to Eq. 2. Forward calculation used the code of the authors.

Furthermore, the apparent resistivity is calculated by

$$\rho_\tau(t) = \frac{\mu_0}{4\pi t}\left(\frac{2\mu_0 Mq}{5t\frac{dB(t)}{dt}}\right)^{2/3} \tag{3}$$

where, $\rho_\tau(t)$ is the apparent resistivity of the detected medium, M is transfer magnetic moment, q is receiver magnetic area, and B is the magnetic induction.

$$\mu_0 = 4\pi \times 10^{-7} H/m,\ B(t) = \mu_0 H \tag{4}$$

where H is the magnetic field calculated by Eq. 2.

The depth of detected target is calculated by

$$h_\tau = \left(\frac{3Mq}{16\pi V(t)S_t}\right)^{1/4} - \frac{t}{\mu_0 S_t} \tag{5}$$

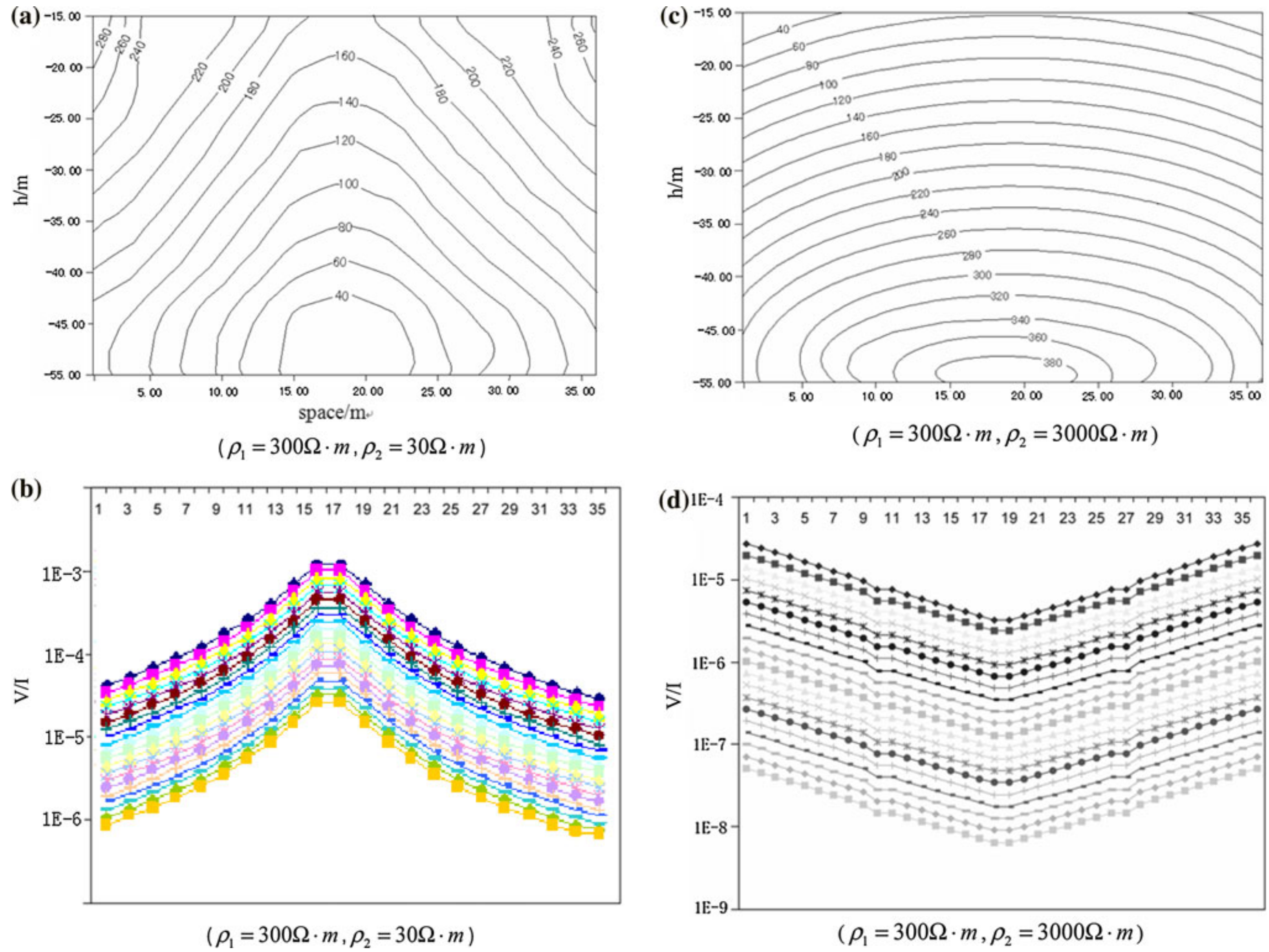

Fig. 2 Apparent resistivity contour of 3-D resistance cave at 50 m depth from calculated result of conductive and resistance models. **a** Apparent resistivity contour of conductive body. **b** Multi-channel TEM curve of conductive body. **c** Apparent resistivity contour of resistance body. **d** Multi-channel TEM curve of resistance body

where $V(t)$ is secondary voltage, and

$$V(t) = \frac{\mathrm{d}B(t)}{\mathrm{d}t} q$$

$$S_\tau = \frac{16\pi^{1/3}}{(3Mq)^{1/3}\mu_0^{4/3}} \frac{[V(t)]^{5/3}}{[V(t)]^{4/3}}. \quad (6)$$

To check the ability of using TEM to survey underground caves, several models are designed to simulate the TEM responses at different conditions, which include conductive and resistive caves at different depths and sizes. The loop source configuration has been employed in these models, and the integral functions are used in numerical calculation.

At first, two kinds of models, 3 m × 1 m × 1 m 3-D conductive and resistant caves are built. The buried depth is 50 m; the length of the transmitting and receiving loops is 50 m; the transmitting frequency of exciting signal is 25 Hz; and the range of time delay is 0.072–8.64 ms. For both models, during the movement of the transmitting loop from one point to another, the electromagnetic responses in the center of the loop are calculated. The multi-channel curve and the apparent resistivity contour of the 3-D conductive cave ($\rho_1 = 300\,\Omega\,\mathrm{m}$, $\rho_2 = 30\,\Omega\,\mathrm{m}$) are shown in Fig. 2; and it is clear that the response values of the conductive body are larger than that of host rock.

Field survey experiments based on TEM

Nowadays, during the fast economic development, a large number of coal mines are being developed all over China. This causes many geologic hazards for the inhabited environment of humans; for example, Fig. 3 shows the cracks of the building in a village near a large coal mine in Yun Nan Province, China.

In order to investigate why cracking of the buildings and subsidence of ground occurred in these villages, and to

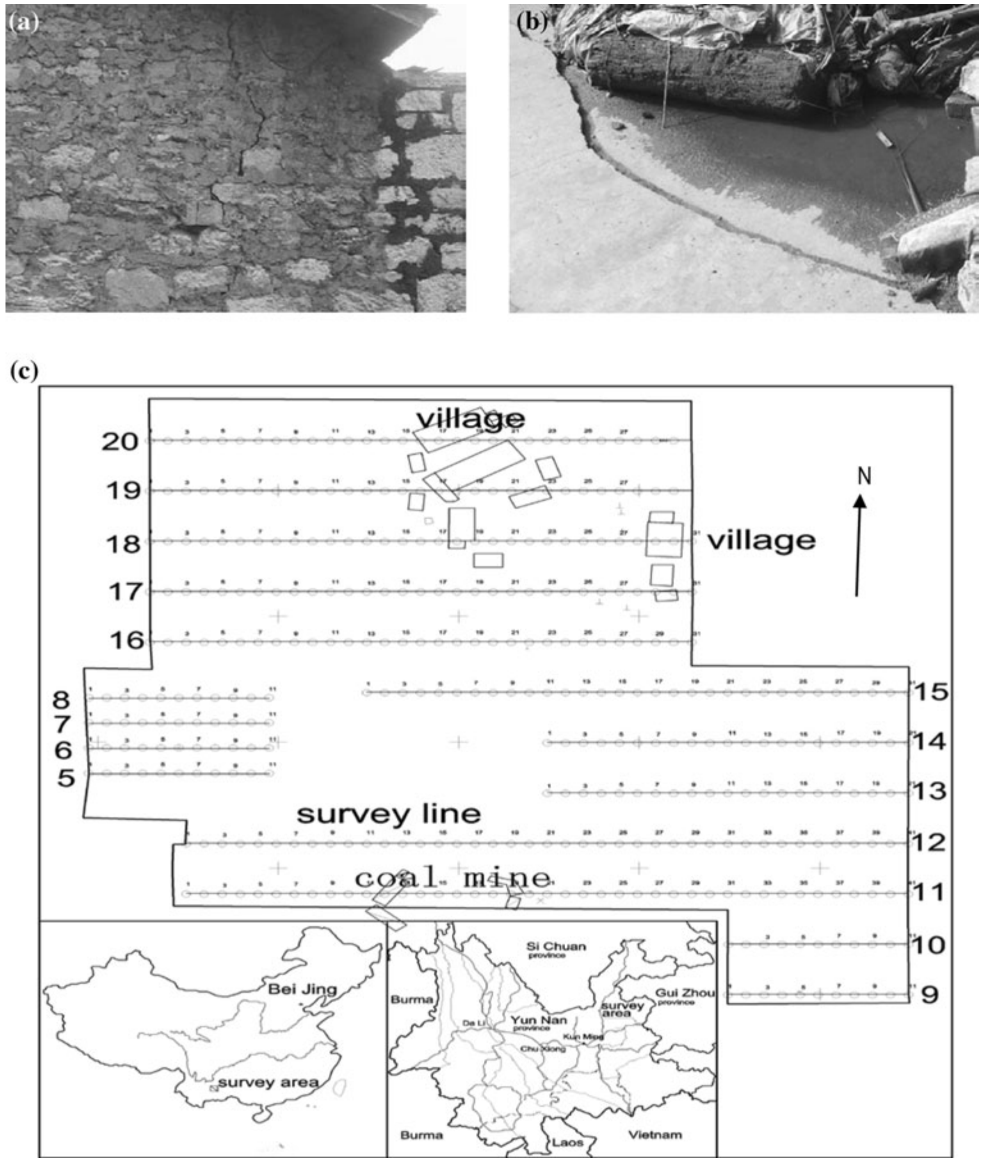

Fig. 3 Geological hazards of buildings and the survey location in the study. **a** Wall crack of the village building. **b** Ground subsidence of the village yard. **c** Selected location for survey experiment

ensure that the coal company takes responsibility for these geologic hazards, the developed TEM technique was applied to survey the above-mentioned geologic hazards. This can provide scientific information for the local government to control the geologic hazards. The goal and task of these researches are to locate the extension range and distribution of the subsidence and ascertain whether the geologic hazard occurred in the villages or were caused by the coal mine.

The measurement consists of 16 electric lines of a total length of 1,700 m; central-loop sounding was employed to survey at an interval of 5 m along every line. The size of the transmitter loop is 100 m $\times$ 100 m and the receiver was a vertical coil sensor with 2,000 m^2 effective area at the center of the measure system. The transmitting current is 10 A with bipolar rectangular wave and the 50% duty-cycle, and a transient electromagnetic receiver. The MSD-1 instrument made in China was used for the data collection. Finally, the collected data were recorded in 100 overlapping time ranges from 0.072 to 8.64 ms. After the measured field data were processed, the contour lines of apparent resistivity of survey line 12 is shown in Fig. 6.

In Fig. 4a, one can find that the resistivity value is different along the contour drawing at 60 m depth from point 140 to point 200. In Fig. 4b, the high resistivity value among point 140 and point 200 indicates the location of ground subsidence, and can be explained as the responses of the air-filled tunnel caused by the coal mine. To verify the results, the drilling test is performed at point 150 of line 12, and the result shows that the depth of the top of buried tunnel is 62 m which agrees with the result of the model.

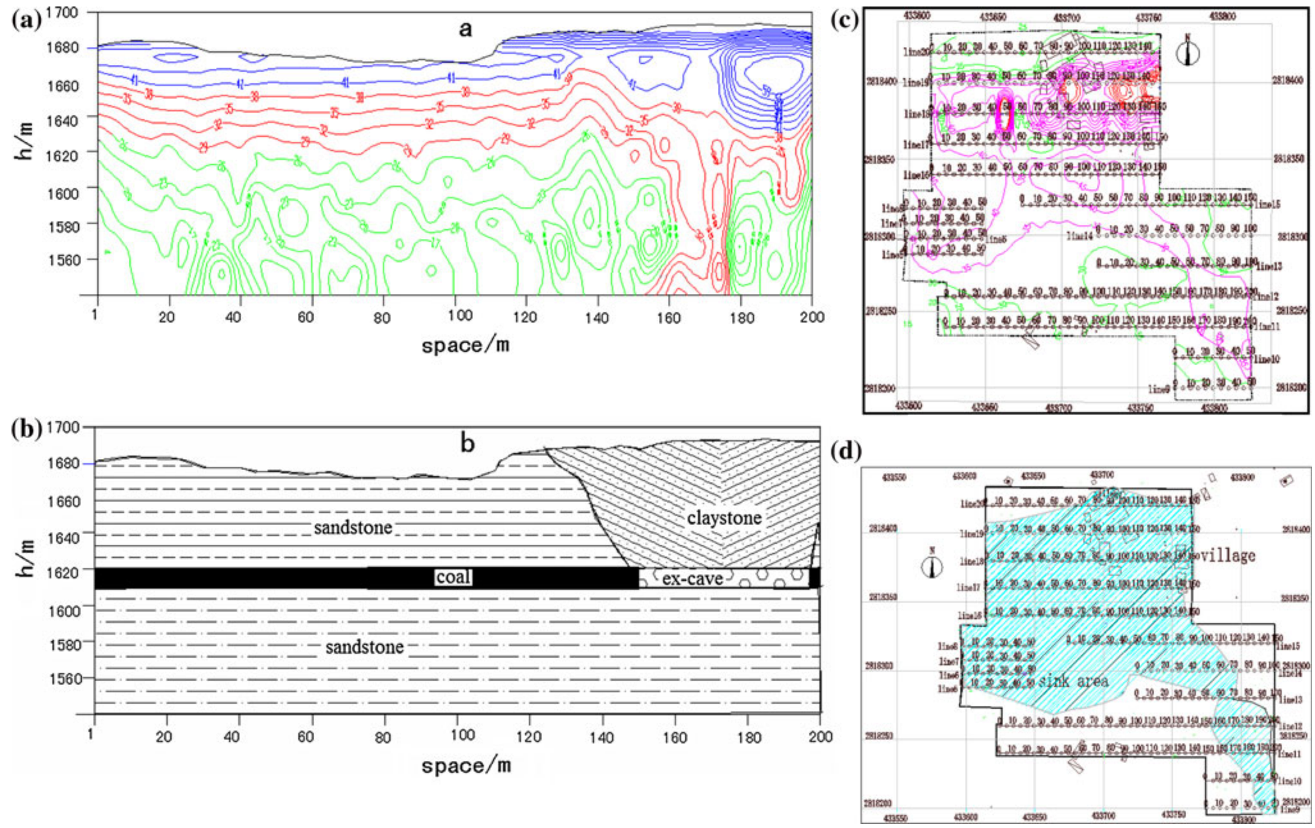

Fig. 4 Apparent resistivity distributing and detected geological status. **a** Geodesic variation of the apparent resistivity at deep direction. **b** Geological structure status at deep direction obtained by surveyed data. **c** Distribution of the apparent resistivity at horizontal direction. **d** Geological structure status at horizontal direction obtained by surveyed data

The plane distribution of apparent resistivity values for the whole detected area is shown in Fig. 4c; the geological structure indicated by the apparent resistivity is given in Fig. 4d. Results show that ground subsidence caused by coal mine besieges most of the village, and clearly indicates that ground subsidence is south of the coal mine. According to the field survey data, it can be confirmed that the building cracks in the village are caused due to the coal mine.

Conclusions

Fast and accurate detection of the diversified underground 3-D cave is very important in highway and railway constructions, and in the survey of geological hazards such as ground subsidence. In this paper, an effective technique, TEM method, is presented. The developed integral function method can be used to calculate the response distribution of the transient electromagnetic for a complex underground 3-D cave, such that the position and the boundary of the cave can be determined. Through considering both high resistive and conductive caves, the ability of using the TEM method to detect the air-filled underground cave is checked, meanwhile, the detection results of the TEM method is also coincident with the drilling survey data. The results show that the developed theory and technique presented in this paper are feasible and effective for the survey of complex ground geological structures.

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