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Joint inversion of TEM and DC in roadway advanced detection based on particle swarm optimization

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ABSTRACT

Transient electromagnetic method (TEM)and direct current method (DC)are two key widely applied methods for practical roadway detection, but both have their limitations. To take the advantage of each method, a synchronous nonlinear joint inversion method is proposed based on TEM and DC by using particle swarm optimization (PSO)algorithm. Firstly, a model with double low resistance anomaly and interference is constructed to test the performance of the method. Then the independent inversion and joint inversion are calculated by using the model built above. It is demonstrated that the joint inversion helped in improving the interpretation of the data to get better results. It is because that the suppression of interference and separation of the resistivity anomalies ahead and the back of the roadway working face using the proposed method. Finally, the proposed method was successfully used in a coalmine in Huainan coalfield in east China to demonstrate its practical usefulness.

1. Introduction

The water-bearing faults, caves, fracture and mined-out area in front of roadway/tunnel working face influence working efficiency and tunneling safety greatly in the tunneling work of mine roadway and transportation tunnels. Accurate detection of these geological anomalies is an important way to predict disasters and ensure the engineering safety.

The geophysical methods in roadway advanced detection including seismic method, transient electromagnetic method (TEM), direct current electrical method (DC), induced polarization method, ground penetrating radar (GPR)and infrared measurement of temperature etc. TEM and DC are two main methods for detecting water-bearing bodies. The research on TEM in whole space used in roadway advanced detection are no more than 10 years, and the basic theories and data processing method are immature. Besides, the anomalies ahead and the back of the roadway front overlap together and are difficult to separate, which greatly affects the practical interpretation results(Yu et al., 2007; Cheng et al., 2014a; Cheng et al., 2014b). The study of DC is focused on application instead of theory, and the detection ability is controversy(Huang et al., 2007; Han et al., 2010). TEM and DC belong to induced electrical method and conductive electrical method respectively, which makes their response characteristics different. The joint inversion using the two methods can make full use of their advantages to improve the detection precision and resolution for better results.

Joint inversion is an important method of integrated geophysical quantitative interpretation. It can be divided into joint inversion based on same physical properties and joint inversion based on different physical properties. Many researchers publish their work on joint inversion based on same physical properties (Wang, 1999; Sharma and Kaikkonen, 1999; Horspool et al., 2006; Dal Moro and Pipan, 2007; Abubakar et al., 2009). Others focus on joint inversion based on different physical properties (Colombo and Stefano, 2007; Gallardo and Meju, 2007; Moorkamp et al., 2011; Peter et al., 2012; Peng et al., 2013; Wan et al., 2013). Joint inversion of TEM and DC based on the same physical properties discussed by Raiche et al. (1985) and Yang et al. (1999). Raiche et al. (1985) accomplished 1-D joint inversion of synthetic and field TEM and DC data, showing improved interpretation of layered-earth parameters, the final model is less dependent upon starting guesses, and non-uniqueness is much less. Yang et al. (1999) carried out joint inversion of TEM and DC data to map the distributions of the freshwater/salt–water interface, presenting that the combined application of DC and TEM can make better detection maps of the freshwater/salt–water interface. All the above mentioned cases are in half space, the study of joint inversion in whole space is few. Dobroka et al. (1991)

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accomplished joint inversion of VSP and DC data in a mine using 1-D 5-layer model. The test of synthetic data and field data shows it can inhibit the equivalence problem of DC, and suppress interference of seismic records.

2. Principles and algorithm of joint inversion

2.1. Complementary of TEM and DC in roadway advanced detection

TEM and DC advanced detection are complementary in the sensitivity to geological information in the front of roadway working face, the separation to geological anomalies in the front and rear, the sensitivity to conducting and resistive bodies, equivalence problem, volume effect and detection range.

DC advanced detection is less sensitive to geological information in the front of the roadway working face, but it can separate geological anomalies in front and rear, and have the same sensitivity to conducting and resistive bodies, while, TEM advanced detection is sensitive to both geological information in front and rear, but cannot separate them, and it is sensitive to conducting bodies but not to resistive bodies. The combination of two methods can provide improved interpretation to get better results.

In DC and TEM advanced detection, the response characteristics are similar when thickness and resistivity are composite values (for conducting layer it is the ratio of thickness and resistivity, for resistive layer is the product of thickness and resistivity), this equivalence problem has a great effect to inversion results. Besides, the volume effect leads to low resolution of TEM inversion results. The combination of two methods can improve detection precision and resolution by avoiding the equivalence problem and volume effect.

The detection ranges of TEM and DC are both 100 m nearby the roadway working face, and the detection blind zone of TEM is the zone where DC has a better detecting effect.

2.2. Improved particle swarm optimization

PSO is a non-liner optimization method developed in recent years, and performs well in geophysical inversion (Shi et al., 2009; Cheng et al., 2014a; Cheng et al., 2014b).

Assuming a swarm is made up of m particles, and the search space is with n dimensions, so the particle position is a n-vector. The parameters in the kth iteration can be expressed as:

The velocity of the ith particle:

$$V_i^k = \left(v_{i,1}^k, v_{i,2}^k, \ldots v_{i,j}^k, \ldots v_{i,n}^k\right) \tag{1}$$

The position of the ith particle:

$$X_i^k = \left(x_{i,1}^k, x_{i,2}^k, \ldots x_{i,j}^k, \ldots x_{i,n}^k\right) \tag{2}$$

The personal best position of the ith particle:

$$PbestX_i^k = \left(pbestx_{i,1}^k, pbestx_{i,2}^k, \ldots, pbestx_{i,j}^k, \ldots pbestx_{i,n}^k\right) \tag{3}$$

The global best position:

$$GbestX^k = \left(gbestx_1^k, gbestx_2^k, \ldots, gbestx_j^k, \ldots gbestx_n^k\right) \tag{4}$$

where, particle number $i = 1, 2, \ldots\ldots, m$, iteration times $k = 1, 2, \ldots\ldots, iter\max$, $iter\max$is the allowable maximum iteration times.

In the beginning, initialize m particles randomly within the search space as initial value of iteration. The position of initialized particles is as Eq. (2), and the velocity is as Eq. (1). After that, particles update their velocity and position based on the following equations (Shi et al., 2009).

$$v_{i,j}^{k+1} = \omega \cdot v_{i,j}^k + c_1 \cdot r_1 \cdot \left(pbestx_{i,j}^k - x_{i,j}^k\right) + c_2 \cdot r_2 \cdot \left(gbestx_j^k - x_{i,j}^k\right) \tag{5}$$

$$x_{i,j}^{k+1} = x_{i,j}^k + v_{i,j}^{k+1} \tag{6}$$

where, j is the dimension of search space, $i, k, v_{i,j}^k, x_{i,j}^k, pbestx_{i,j}^k, gbestx_j^k$ are defined as before. c_1, and c_2 are defined as learning factors, usually, $c_1 = c_2 = 2$,r_1, and r_2 are two uniformly distributed random numbers between 0 and 1. ω is inertia factor. Eq. (5)and Eq. (6) form the basic equations of PSO algorithm. In order to improve optimization results, combined with the requirement of joint inversion, the following improvement strategies have been proposed (Cheng et al., 2014a; Cheng et al., 2014b):

$$v_{i,j}^{k+1} = \omega \cdot v_{i,j}^k + \phi_1\left(pbestx_{i,j}^k - x_{i,j}^k\right) + \phi_2\left(gbestx_j^k - pbestx_{i,j}^k\right) \tag{7}$$

Where, $\omega = 1 + \varphi_1 + \varphi_2 - \sqrt{(\varphi_1 + \varphi_2)(2 + \varphi_1 + \varphi_2)}$, $\phi_1 = c_1 \cdot rand()$, $\phi_2 = c_2\ rand()$, and $rand()$ is as random number of the range (0, 1).

Eq. (6)and (Eq. 7) form the PSO inversion algorithm in this paper.

2.3. Principles and algorithm of joint inversion

Forward modeling is the foundation of inversion. The TEM forward algorithm is discussed by paper (Krivochieva and Chouteau, 2002), and DC forward algorithm is demonstrated by paper(Ge, 1994).

A whole space 1-D upright layered model is constructed. The electricity of each layer is homogeneous and isotropic. The model includes n layers, and the thickness of the first layer and n-layer is infinite. Model parameters can be written as:

$$X = [\rho_1, \rho_2, \cdots, \rho_{n-1}, \rho_n, h_2, h_3, \cdots, h_{n-2}, h_{n-1}] \tag{8}$$

where, $\rho_1, \rho_2, \cdots, \rho_{n-1}, \rho_n$ are the resistivity of each layer. $h_2, h_3, \cdots, h_{n-2}, h_{n-1}$ are the thickness from the second layer to n − 1 layer. The total number of model parameters is 2n − 2.

Y^{TEM} is defined as forward response value of TEM advanced detection including a magnetic intensity value. f_{TEM} is defined as operator of TEM advanced detection, then TEM advanced detection forward equation can be expressed as:

$$Y_k^{TEM} = f_{TEM}(X), k = 1, 2, \cdots, a-1, a. \tag{9}$$

Y^{DC} is defined as forward response value of DC advanced detection, including b apparent resistivity value. f_{DC} is defined as operator of DC advanced detection, then DC advanced detection forward equation can be expressed as:

$$Y_k^{DC} = f_{DC}(X), k = 1, 2, \cdots, b-1, b. \tag{10}$$

In order to do synchronous joint inversion, we treat TEM advanced detection and DC advanced detection as a whole forward process. Y^{JOINT} is defined as joint forward response value of TEM and DC, including a + b response values. f_{JOINT} is defined as joint forward operator, then joint forward equation can be expressed as:

$$Y_k^{JOINT} = f_{JOINT}(X), k = 1, 2, \cdots, a+b-1, a+b \tag{11}$$

where, $f_{JOINT} = \begin{cases} f_{TEM}, 1 \le k \le a \\ f_{DC}, a < k \le a+b \end{cases}$.