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The time-domain electromagnetic inversion method based on NN

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Abstract

The time-domain electromagnetic (TEM) detection method has important applications in geological structure exploration, mineral resource exploration, and other fields. The inversion method for TEM data of the Cole-Cole model for induced polarization (IP) effect has important research value. In this paper, a TEM inversion method based on a fully connected neural network (NN) is studied, which extracts parameter information of the Cole-Cole model. The loss function of the fully connected NN is researched, and the performance of NN is optimized. The effectiveness of the optimized fully connected NN inversion method was verified through a theoretical model, and the inversion results are compared with the results of traditional conductivity inversion method based on back propagation NN (BPNN). The results show that the method proposed in this paper improves the inversion accuracy of the conductivity parameter.

Keywords

NN, inversion, conductivity, TEM.

1. Introduction

The time-domain electromagnetic (TEM) detection method is an effective geophysical exploration method[1-3]. This method obtains the underground geological information by inverting TEM data. The sign reversal phenomenon may happen in the TEM field data. After a large number research, it has been found that the sign reversal phenomenon is caused by the induced polarization (IP) effect[4-6]. The complex conductivity models have been constructed for IP effect[7-10], which includes parameter information such as conductivity and polarizability. For IP effect, it is necessary to study inversion methods includes polarization model parameters for TEM data.

Neural network (NN) with strong learning and adaptability is a feature learning method. In recent years, NN have been continuously developed and have been applied to the inversion of TEM data[11-14]. The NN method can be effectively applied to TEM data inversion. In this paper, the TEM inversion method based on NN is studied for IP effects, which extracts parameter information such as the conductivity and polarizability of the Cole-Cole model.

2. The TEM response of the Cole-Cole model

To approximate the IP effect of underground media, the complex conductivity models have been constructed. The most classic model among them is the Cole-Cole model[8], the frequency-domain expression of the conductivity is expressed as:

$$\sigma(\omega)=\sigma_0\left(1+\eta\frac{(i\omega\tau)^c}{1+(1-\eta)(i\omega\tau)^c}\right) \tag{1}$$

where *i* is the imaginary unit, ω is the angular frequency, σ_0 is the conductivity at zero frequency, η is the polarizability, *c* is the frequency dependence, and τ is the characteristic time constant. The range of values for the polarizability η and frequency dependence *c* is zero to one.

For a n-layer underground media model, the conductivity and thickness of each layer are σ_1, d_1, σ_2, d_2, ..., σ_n, d_n, $d_n \to \infty$. The wire source is laid on the ground, and the length is 2L. The center point of the wire source is the coordinate origin, and the wire extends along the x-axis direction. The center perpendicular of the wire source is the y-axis, and the z-axis is the vertical offset, positive up. The conductivity expression of the Cole-Cole model is substituted into the Maxwell equation, and the fractional order diffusion equation is derived. The vertical component of the magnetic field is obtained through further derivation, and it is expressed as:

$$H_z = \frac{I}{4\pi}\int_{-L}^{L}\frac{y}{R}\int_0^{\infty}(1+r_{\mathrm{TE}})e^{u_0 z}\frac{\lambda^2}{u_0}J_1(\lambda R)\,d\lambda\, dx' \tag{2}$$

where *I* is the emission current, *R* is the source-receiver distance, r_{TE} is the reflection coefficient, J_1 is the first-order Bessel function. $u_0 = (\lambda^2 - k^2)^{1/2}$, where k is the wave number of the polarized medium, $k = \left(-i\omega\mu\sigma(\omega)\right)^{1/2}$.

3. The inversion method based on NN

The information of underground media can be obtained through the inversion of TEM data. Fully connected neural networks can handle a large amount of data in unknown mapping relationships. For IP effect, an inversion method based on a fully connected NN is studied. The input of the fully connected neural network is TEM data, and the output is parameter information of the Cole-Cole model.

According to the known geological data information, different medium models with multiparameter changes are constructed, and TEM responses are calculated. A sample set of TEM responses and models is constructed. The NN structure is optimized and training functions is selected based on the requirements of a fully connected NN. The fully connected NN is trained using the sample set to construct mapping relationships between inputs and outputs. To improve the inversion accuracy, the loss function of the fully connected NN is studied, which is the evaluation of errors between predicted and true values. Then the performance of the fully connected NN is optimized by increasing sample sets and adjusting the NN structure. The TEM data are inverted by the optimized fully connected NN, and the outputs are the conductivity σ_0 and polarizability η.

4. Validation

To verify the effectiveness of the TEM inversion method based on the optimized fully connected NN, a layered model of the Cole-Cole model was designed. The parameters of the three-layer model are shown in Table 1. The conductivity σ_0 of the first layer is 0.01 S/m. The conductivity of the Cole-Cole model layer is 0.1 S/m, the polarizability is 0.1, and its depth is -200 m to -220 m. The conductivity of the third layer is 0.01 S/m. The parameters of the TEM detection method are: the length of the grounded wire source is 1000 m, the current is I = 10 A, and the ground receiving position is set as x = 0 m, y = 200 m. The TEM data are inverted by the optimized fully connected NN. The optimized fully connected NN is abbreviated as OFCNN. The inversion results of the traditional conductivity inversion method based on back propagation NN (BPNN) is used for comparison. The results are shown in Fig. 1.

Table 1. Parameters of the three-layer model of the Cole-Cole model

	conductivity (S/m)	polarizability	layer thickness (m)
first layer	0.01	0	200
second layer	0.1	0.1	20
third layer	0.01	0	INF

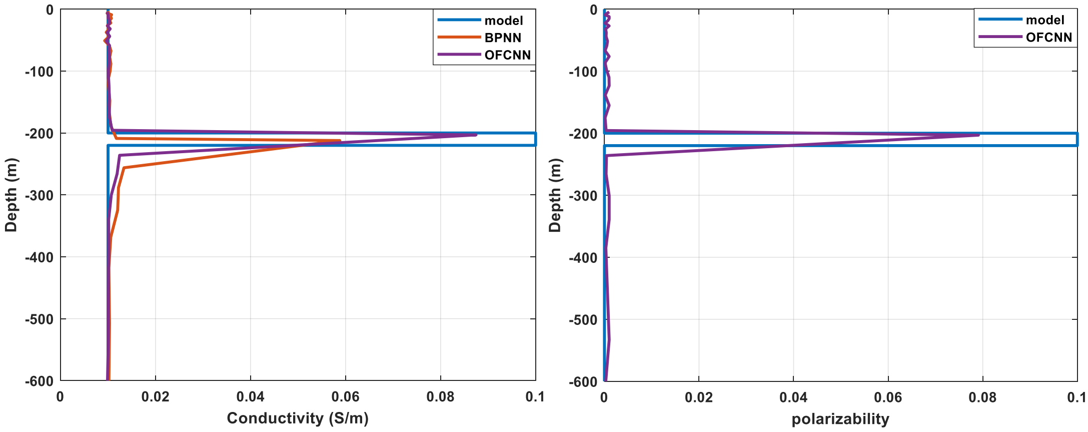

Fig. 1. Inversion results of the three-layer model. (a) conductivity, (b) polarizability.

Fig. 1 shows the conductivity and polarizability results, the blue lines are the theoretical model, the orange lines are the results of the BPNN, and the purple lines are the results of the OFCNN. The OFCNN can effectively extract conductivity and polarizability parameter information. The results show that conductivity of the three-layer media model can be detected, however, the results of the OFCNN are closer to the theoretical model. To quantitatively estimate the inversion results, the relative error (RE) of the conductivity results was calculated. The average RE of conductivity results of the OFCNN is 3.38%, and the average RE of conductivity results of the BPNN is 6.69%. Therefore, the effectiveness of the OFCNN is verified, and the accuracy of the conductivity in OFCNN inversion method has been improved by at least 3% compared to traditional conductivity inversion method based on BPNN.

$$\mathrm{RE}=\frac{\left|\hat{\rho}(n)-\rho(n)\right|}{\rho(n)}\times 100\% \tag{3}$$

5. Conclusion

A fully connected NN is trained using the sample set of TEM responses of the Cole-Cole model. The loss function of the fully connected NN is studied, and the performance of NN is optimized. The optimized fully connected NN is established, and it can be used to extract the conductivity and polarizability from TEM data. The TEM inversion method based on the optimized fully connected NN is verified through a three-layer model of the Cole-Cole model. The results show that the optimized fully connected NN can effectively extract conductivity and polarizability parameter information. The inversion results are compared with the results of the traditional conductivity inversion method based on BPNN. The results show that the optimized fully connected NN improves the inversion accuracy of the conductivity parameter.

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