Pseudo wavefield extraction method of multi-channel transient electromagnetic method (MTEM)

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***Abstract*—The data acquisition mode of Multi-channel transient electromagnetic method (MTEM) is similar to that of seismic method, it is significant to research pseudo-seismic wave-field extraction technology for MTEM data. Basing on singular value decomposition method and regularized method, we propose correlation stacking method to extract pseudo-seismic wavefield of MTEM data. Firstly extracting pseudo-seismic wave-field of whole-time-domain MTEM data with regularized method, then extracting pseudo-seismic wavefield of each time quantum determined with the same method. Finally, stacking the pseudo-seismic wavefield data according to their correlation, and regard the stacked result as the final extraction result. The extraction result of measured MTEM data with correlation stacking method is more smooth than that of singular value decomposition method and regularized method.**

Keywords*—*MTEM; pseudo wavefield extracting; correlation stacking

I. Introduction

Multi-channel transient electromagnetic method (MTEM) is developing rapidly in recent years [1]. This kind of data acquisition mode is similar to that of seismic exploration, so it can obtain similar data format which is similar to that of seismic exploration. In this case, pseudo-seismic interpretation technology is suitable for the interpretation of MTEM data. So it is significant to research pseudo-seismic wavefield extraction method for MTEM data.

In this paper, a new pseudo-seismic wavefield extraction method, correlation stacking method, is proposed. We compare the pseudo-seismic wavefield extraction result of simulated data with this new method to that of singular value decomposition method and preconditioned regularized conjugate gradient method. The comparison result shows that the extraction result of correlation stacking method is more smooth, and the anti-interference ability is stronger.

Usually, the response collected by MTEM system can be expressed in this form [2]:

$$a_k(x_s,x_r,t)=i(k,x_s,t)*r(x_r,t)*g(x_s,x_r,t)+n(x_r,t) \tag{1}$$

where, $a_k(x_s,x_r,t)$ denotes the total response collected, $i(k,x_s,t)$ denotes source current, $r(x_r,t)$ denotes the system response of recording system, k denotes k(th) data collection, $g(x_s,x_r,t)$ denotes the earth impulse response, $n(x_r,t)$ denotes noise, x_s denotes the source position, x_r denotes the acquisition position, t denotes time. According to Eq. (1), the earth impulse response can be extracted from the collected data through deconvolution.

The corresponding mathematical relation between time domain diffusion field and pseudo wavefield[3] ,

$$E(x,y,z,t)=\frac{1}{2\sqrt{\pi t^3}}\int_0^\infty \tau e^{-\frac{\tau^2}{4t}}U(x,y,z,\tau)d\tau \tag{2}$$

In Eq.(2), $E(x,y,z,t)$ denotes diffusion field which obeys diffusion equation, $U(x,y,z,\tau)$ denotes pseudo wave-filed which obeys wave equation, τ denotes pseudo time. The MTEM earth impulse response is diffusion field, so by solving Eq.(2), we can obtain pseudo wave-filed of MTEM earth impulse response.

In this paper, methods for pseudo wave-field extraction are introduced and results of these methods are compared for choosing the optimal method.

II. MTEM Pseudo Wave-Field Extraction Method

A. Singular Value Decomposition (SVD) Method

The discrete numerical integration form of Eq. (2) is,

$$E(x,y,z,t_i)=\sum_{j=1}^{n}U(x,y,z,\tau_j)a(t_i,\tau_j)h_j \tag{3}$$

where, $a(t_i,\tau_j)=\frac{1}{2\sqrt{\pi t_i^3}}\tau_j e^{-\frac{\tau_j^2}{4t_i}}$, h_j denotes integral coefficient.

The matrix form of Eq.(3) is,

$$\mathbf{K}_{m\times n}\mathbf{U}=\mathbf{E} \tag{4}$$

In Eq. (4), $\mathbf{U}=(U_1,U_2,...U_n)$, $\mathbf{U}=(E_1,E_2,...E_n)$, $\mathbf{K}_{m\times n}$ is coefficient matrix.

Conduct singular value decomposition for coefficient matrix $K_{m\times n}$,

$$\mathbf{K}_{m\times n} = \mathbf{L}_{m\times m}\mathbf{S}_{m\times n}\mathbf{V}_{n\times n}^{T} \tag{5}$$

In which $\mathbf{L}_{m\times m}, \mathbf{V}_{n\times n}$ are orthogonal matrixs, $\mathbf{S}_{m\times n}$ is diagonal matrix. In this case,

$$\mathbf{U} = \mathbf{V}_{n\times n}\mathbf{S}_{m\times n}^{-1}\mathbf{L}_{m\times m}^{T}\mathbf{E} \tag{6}$$

After singular value decomposition is conducted, the morbid degree of coefficient matrix will not increase in the solving process. At the same time, the coefficient matrix is converted into diagonal matrix, which can decrease computer's operation time.

B. Regularized Method

For conjugate gradient method, the coefficient matrix must be positive definite matrix. In order to meet this requirement, convert Eq. (4) to,

$$\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}\mathbf{U} = \mathbf{K}_{m\times n}^{T}\mathbf{E} \tag{7}$$

In Eq. (7), $\mathbf{K}_{m\times n}^{T}$ is the transposed matrix of $\mathbf{K}_{m\times n}$. If $\mathbf{K}_{m\times n}$ is column full rank matrix, $\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}$ will be positive define matrix. However, the condition number of $\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}$ is bigger than that of $\mathbf{K}_{m\times n}$, so over relaxation precondition method is used to reduce the condition number. Then construct preconditioner as follows,

$$M(\alpha) = (C_1 + \omega C_2)^{-1}C_1^{-1}(C_1 + \omega C_3) \tag{8}$$

In Eq. (8), C_1 is the diagonal element of $\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}$, $\mathbf{C}_2$ is the lower triangular element of $\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}$, $\mathbf{C}_3$ is the upper triangular element of $\mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n}$, ω is a parameter within（0,2).

After the preconditioner has been selected, regularization method can be used for iterative solution of the equations. The iterative equation used here is,

$$\mathbf{M}(\alpha)^{-1}\mathbf{K}_{m\times n}(\alpha)x = \mathbf{M}(\alpha)^{-1}(\alpha x^{k} + \mathbf{E}) \tag{9}$$

In Eq. (9), α is the regularization factoe, x^{k} is the value of the $k(\mathrm{th})$ iteration, the initial value of x is selected as:

$$\mathbf{K}_{m\times n}(\alpha) = \alpha\mathbf{I} + \mathbf{K}_{m\times n}^{T}\mathbf{K}_{m\times n} \tag{10}$$

C. Correlation Stacking Method

In order to reduce the false peak of the pseudo wavefield extracted with regularized method to get more smooth pseudo wavefield waveform, we introduce correlation stacking method for pseudo wavefield extraction. The specific steps are as follows:

Step 1: Using regularized method on full time domain data (Fig.1) to extract pseudo wavefield, the result is $\mathbf{U}_{\mathbf{all}}$;

Step 2: Choose a time window and use preconditioned regularized conjugate gradient method on the data in this time window (Fig. 2) to extract pseudo wavefield, the result is $\mathbf{U}_{\mathbf{1}}$;

Step 3: Move the choosed time window for a time-channel unit and use preconditioned regularized conjugate gradient method on the data in this time window to extract pseudo wavefield, the result is $\mathbf{U}_{\mathbf{2}}$;

Step 4: Moving the time window again for a time-channel unit again, and repeat step (3) until moving to the last time window, then pseudo wavefield $\mathbf{U}_{\mathbf{3}}, \mathbf{U}_{\mathbf{4}}, \ldots, \mathbf{U}_{\mathbf{n-m+1}}$ extracted from each time window can be obtained;

Step 5: Conduct correlation analysis on $\mathbf{U}_{\mathbf{n}}(\mathrm{n} = 1, 2, \ldots, \mathrm{n}-\mathrm{m}+1)$ and $\mathbf{U}_{\mathbf{all}}$, if their correlation is bigger than a threshold value α, retain $\mathbf{U}_{\mathbf{n}}$, or abandon $\mathbf{U}_{\mathbf{n}}$. The correlation between $\mathbf{U}_{\mathbf{n}}$ and $\mathbf{U}_{\mathbf{all}}$ is defined as,

$$\eta = \frac{|\mathbf{U}_{\mathbf{n}} \cdot \mathbf{U}_{\mathbf{all}}|}{|\mathbf{U}_{\mathbf{n}}| \cdot |\mathbf{U}_{\mathbf{all}}|}$$

Step 6: Stack all the retained $\mathbf{U}_{\mathbf{n}}$ with $\mathbf{U}_{\mathbf{all}}$, and regard the stacking result as the finial result of pseudo wavefield extraction.

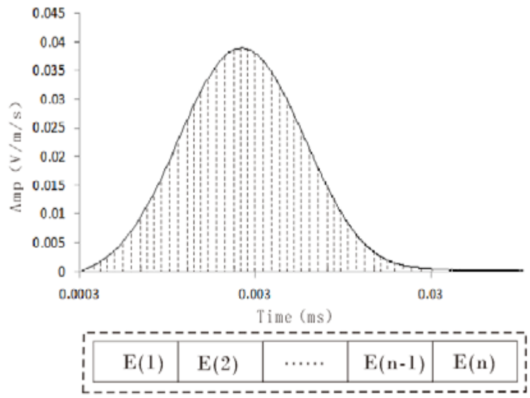


Fig. 1. Diagram of pseudo-wavefield extraction integral window (full-time domain data)

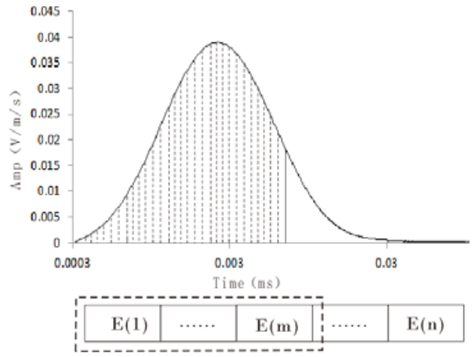


Fig. 2. Diagram of pseudo-wavefield extraction integral window 1

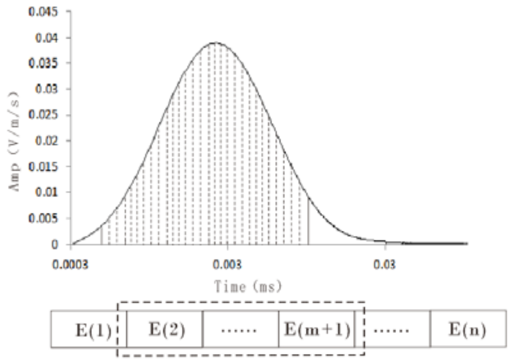


Fig. 3. Diagram of pseudo-wavefield extraction integral window 2

III. SIMULATED DATA ANALYSIS

In order to verify the effect of correlation stacking method, use three kinds of the extraction methods mentioned above to extract pseudo wavefield of MTEM simulated data and compare the results. The model used is shown in Fig.4. The model is a two horizon layer model, the interface of which is 200m. The resistivity of the upper layer is 100 Ω · m , while the resistivity of the lower layer is 10 Ω · m . The transmitting wire is 500m long, the source current is 10A. The collecting point is 1000m away from the midpoint of the transmitting wire. The synthetic data is obtained using finite difference time domain (FDTD) method [4]. In order to compare the anti-interference ability of these three methods, the Gaussian noise whose standard deviation is 5% is generated with the noise model proposed by Munkholm and Auken (1996) is added into the data.

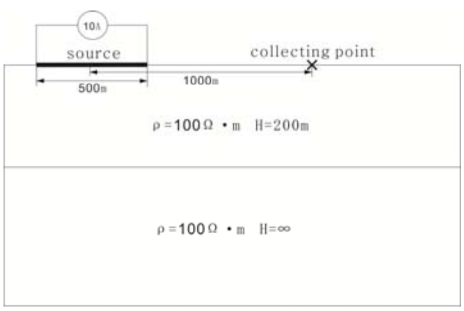
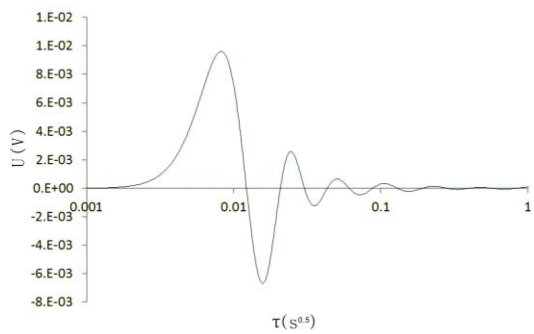


Fig. 4. Model of MTEM simulation data

Fig. 7 shows the pseudo wavefield extraction results with singular value decomposition method, in which Fig.7 (a) is the extraction result of the data without noise and Fig.7(b) is the extraction result of the data with 5% Gaussian noise. Fig. 5 indicates that the pseudo wavefield extracted with singular value decomposition method has false peak. And when noise exists, the waveform throbs sharply.

Fig. 6 shows the pseudo wavefield extraction results with preconditioned regularized conjugate gradient method, in which Fig. 6 (a) is the extraction result of the data without noise and Fig. 6 (b) is the extraction result of the data with 5% random noise. Fig. 6 indicates that the pseudo wavefield extracted with preconditioned regularized conjugate gradient method has a stable waveform and obvious peak. However, if there is noise in the data, some false peaks appears in the pseudo wavefield.

(a)



(b)

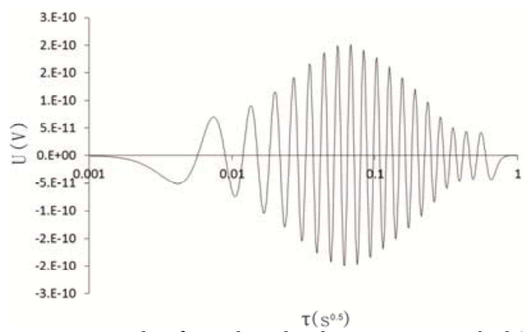
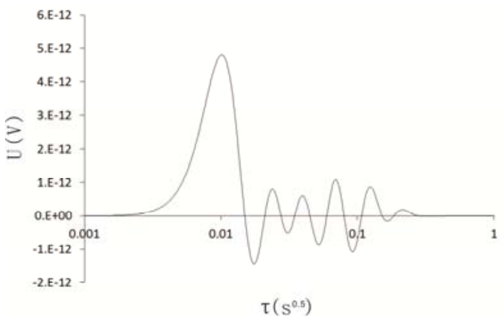


Fig. 5. Extraction results of singular value decomposition method (a) no noise; （b）add 5% noise

(a)



(b)

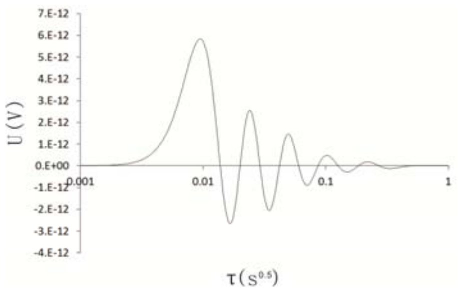
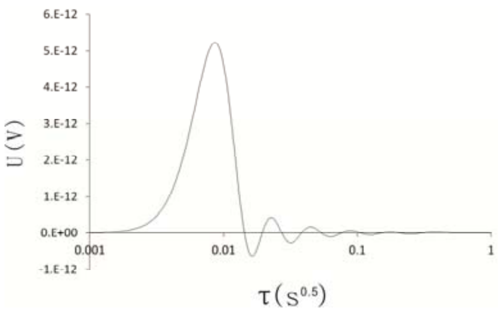


Fig. 6 Extraction results of preconditioned regularized conjugate gradient method. (a) no noise; （b）add 5% noise

(a)



(b)

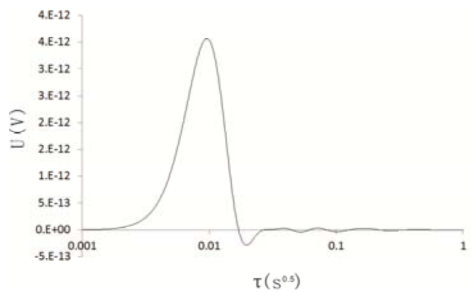


Fig. 7 Extraction results of correlation stack method（a）no noise; （b）add 5% noise

Fig. 7 shows the pseudo wavefield extraction results of correlation stacking method, in which Fig.9(a) is the extraction result of the data without noise and Fig.9 (b) is the extraction result of the data with 5% random noise.

Fig. 9 indicates that the pseudo wavefield extracted from correlation stacking method is more smooth than that of preconditioned regularized conjugate gradient method and the attitude of false peaks are reduced effectively.

IV. CONCLUSION

The extraction result with singular value decomposition method throbs sharply when noise existing, which cause the wave peak undistinguishable. The extraction result and anti-interference ability of preconditioned regularized conjugate gradient method is better than that of singular value decomposition method, but false wave peaks still exist. We introduce correlation stacking method to smooth the extraction result and suppress false wave peaks. Pseudo wavefield extraction result of simulated data and measured data both indicate that the pseudo wavefield extraction result with correlation stacking method is more smooth, and the wave peak is obvious.

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