Transient Electromagnetic Pseudo Seismic Imaging System in Watery Goaf Detection

Hao Qiu1, Yi Mu2, Hui Xu†, Zongyun Shu
1 Mine Safety Technology Branch of China Coal Research Institute, Beijing, 100013, China
2 State Key Laboratory of Coal Resource Efficient Mining and Clean Utilization (China Coal Research Institute), Beijing, 100013, China
3 Beijing Mine Safety Engineering Technology Research Center, Beijing, 100013, China
*Corresponding author’s e-mail: qiuhaogeo@163.com

Abstract. In order to detect accurate watery goaf distribution and impact area in coal mine, and on the base of Transient Electromagnetic detection for Gushuyuan Coal, Simulation of Seismic Processing experimental scheme based on wave field conversion was established. Meanwhile, comparison between traditional transient electromagnetic data processing method and pseudo seismic imaging system was analyzed. The results showed obvious relationship between boundary of watery goaf and geological electrical interface. Pseudo seismic imaging system based on wave field conversion can show more efficiency to distinguish depth and boundary range of watery goaf than traditional Transient Electromagnetic data processing method. Pseudo seismic imaging system can also overcome adverse affection from volume, improve vertical resolution and provide reference for goaf disaster prevention and treatment.

1. Introduction
Mine water disaster is a great security threat to coal mine production. Since it is with rich water and uncertain depth in watery goaf, water inrush disaster probably occurs during mining active process. Water disaster prevention and control is always the focus and different point for mine water control work. Transient electromagnetic method is one of the most effective methods to detect the area of watery goaf. Due to the volume effect to transient electromagnetic method, it appears that low resistance anomaly boundary does not represent the actual boundary of the water rich region in traditional transient electromagnetic apparent resistivity map. It is difficult to determine the boundary of the watery goaf.

The transient electromagnetic imaging technique based on wave field conversion theory provides a new idea for detection of watery goaf by solving physical properties and geometrical parameters of the anomalous body, which traditional transient electromagnetic field can’t provide. An issue that has been investigated by numerous researchers (Levy et al., 1988; Lee et al., 1993; Chen et al., 1999). It is generally accepted that there is a correspondence between diffusion field and wave field of the transient electromagnetic method. Chen et al. (1999) analyzed simple wave field conversion model under half space condition based on wave field conversion theory. Li et al. (2005) designed a normalized method to make converted wave field stable and reliable. Xue et al. (2006) constructed an equivalent conversion relationship between time and frequency domains after theoretical model.
forward calculation, curve comparison, errors analysis and the theoretical discussion about the propagation of diffusion field and wave field. (Li et al., 2005; Xue et al., 2011; Guo et al., 2012) put forward an idea that uses deconvolution technology to eliminate the waveform broadening effect in the wave field conversion. Cheng et al. (2013) studied the method of mine transient electromagnetic synthetic aperture in full space based on idea of synthetic aperture in radar. Cheng et al. (2013) discussed theory of transient electromagnetic field conversion, proposed algorithm of mine transient electromagnetic field conversion and calculated wave field with actual surveying data. Li et al. (2015) studied Kochhoff immigration of transient electromagnetic wave field of the air source device. Cheng et al. (2016) designed an algorithm to convert transient electromagnetic field to the pseudo seismic wave field for advanced detection based on function relationship between spreading electromagnetic field and seismic wave field in whole space.

Previous works have comprehensively studied the conversion algorithm of transient electromagnetic field, but the method of processing the converted wave field data based on wave field conversion theory has not been considered completely. As a common transient electromagnetic detection target, specific detection and analysis method of watery goaf is still to be studied. In this study, a numerical calculation methodology was provided to operate this system based on wave field conversion theory. A new data processing system was designed to deal with transient electromagnetic data in wave field.

2. Methodology

2.1. Conversion equation

Mathematical integral form (Levy et al., 1988; Lee et al., 1993; Chen et al., 1999) between transient electromagnetic field component and its corresponding wave field component is

\[ P(r, t) = \frac{1}{2\sqrt{\pi t^3}} \int_0^{\infty} q e^{-q^2/4t} U(r, q) dq \]  

where, \( P(r, t) \) is TEM component; \( U(r, q) \) is wave field component; \( t \) is TEM time; \( q \) is wave field travel time; \( r \) is field value; The class time variable \( q \) corresponding to the time \( t \) is quantity in \( \sqrt{s} \), and pending wave field \( U(r, q) \) is the quantity in \( 1/\sqrt{\mu \sigma} \), \( \sigma \) is conductivity, \( \mu \) is permeability.

The significance of this conversion can convert the transient electromagnetic field component attenuation curve with time \( t \) into the propagation curve of the wave field with time \( q \). The propagation velocity of this wave field is inversely proportional to the square root of the conductivity, which satisfies wave equation. Physical and geometric parameters can be solved by using data processing methods in seismology.

The conversion equation can be converted to discretization by using the variable step size trapezoidal, where, the matrix form is:

\[ AU = P \]  

\[ U = (U_1, \ldots U_i, \ldots U_n)^T, P = (P_1, \ldots P_i, \ldots P_n)^T \]  

where, \( A \) is \( m \times n \) matrix in Eq. (2). The wave field conversion process can be realized by solving Eq. (2). Eq. (2) is misconception integral equation, which can be calculated by method of matrix decomposition, regularization and etc.

2.2. Pseudo seismic data process imaging

Known from wave field conversion theory, transient electromagnetic field variables are needed to complete convert from diffuse field to wave field. Induced electromotive force can be used to calculate the magnetic induction intensity change rate with time, which can be used to calculate vertical magnetic field components. The data \( t \) and \( P \) in Eq. (1) based on transient electromagnetic diffusion field can be obtained. The wave field value \( U \) of the transient electromagnetic field at time \( q \) can be
solved by Eq. (2). The data of transient electromagnetic wave field can be processed and imaged by various methods in seismic data processing.

When dealing with pseudo seismic data, method of cubic spline interpolation is priority used to interpolate high density wave field conversion data, to make wave field curve smooth and continuous. And cubic spline interpolation can also reduce effect to the following process. The high density interpolation method is defined by cubic spline interpolation. Function \( S(x) \in C[a, b] \) is a cubic polynomial in each node \([x_0, x_1, \ldots, x_n] \), where \( a < x_0 < x_1 < \ldots < x_n = b \) are given nodes, if \( y_j = f(x_j), (j = 0, 1, \ldots, n) \), \( S(x_j) = y_j, (j = 0, 1, \ldots, N) \).

As data collected by transient electromagnetic method is mostly low frequency components in the middle and late stages. Velocity and wavelength of the converted wave field are much larger than those of the seismic wave field, then vertical resolution is reduced. Therefore, deconvolution method is used to deal with wave field conversion data to compress the seismic wavelet and improve the resolution. Deconvolution algorithm is defined by least squares inverse filtering algorithm. The interpolated wave field data is used as an input signal:

\[
\begin{align*}
    b(t) &= (b(0), b(1), \ldots, b(n)) \\
    a(t) &= (a(0), a(1), \ldots, a(m)) \\
    y(t) &= a(t) * b(t) = \sum_{\tau} a(\tau) b(t-\tau) = (y(0), y(1), \ldots, y(M)) \quad M = m + n
\end{align*}
\]

where, \( b(t) \) is input signal in Eq. (4), \( a(t) \) is Inverse filter factor in Eq. (5), \( y(t) \) is output signal in Eq. (5). \( y(t) \) is the output wave field data after deconvolution processing.

Time depth conversion is carried out to solve depth of wave field corresponding to different time according to the velocity of equivalent eddy current loop of the transient electromagnetic field. The wave field conversion curve corresponding to depth is obtained. The time depth conversion algorithm is defined by smoke ring inversion algorithm.

\[
v = \frac{\Delta d}{\Delta t} = \frac{d_j - d_i}{t_j - t_i} = \frac{4}{\sqrt{\pi \mu}} \left[ \sqrt{\frac{\rho_j}{\rho_i}} - \sqrt{\frac{\rho_j}{\rho_i}} \right]
\]

where, \( v \) is the propagation velocity of TEM field. \( \Delta t \) is TEM diffusion field period. \( t \) is TEM time. \( \rho \) is apparent resistivity. \( \mu \) is permeability. The propagation velocity of TEM field in each diffusion field period can be determined by Eq. (7).

\[
D(t) = \int_0^t v(\rho, \tau) d\tau
\]

where, \( \rho \) is apparent resistivity. \( t \) is TEM time. \( D(t) \) is the propagating depth of TEM field. According to the apparent resistivity \( \rho \) and the wave field travel time \( q \) of time series extracted from the transient electromagnetic original data, the depth corresponding to the sampling point of the wave field conversion data at different time can be calculated by Eq. (8).

Finally, correlation analysis is carried out to synthesize the conversion curves of multi measuring points by using synthetic aperture technique to improve the resolution of wave field curve. Figure 1(a) and Figure 1(b) show the process contrast between traditional data processing and pseudo seismic imaging. All the processes of transient electromagnetic pseudo seismic method are carried out under seismic wave field conditions. Seismic wave field is strong in resolution of geometric interface. The method can solve problem that transient electromagnetic method is not enough when resolving the geometrical interface. Pseudo seismic imaging system can be used to determine distribution and boundary of watery goaf.
3. Experimental method

3.1. Experimental background
Working face designed in Gushuyuan Coal Mine 91304 is No.9, working elevation is 630 ~ 660m, average thickness is 1.2m, working face length is 240m, inclined length is 150m, average dip angle is 3°. Figure 2 shows the parameters of 91304 working face. There are No.3 coal seam watery goaf in the upper part of the working face. Water content of the goaf is unknown. Average spacing between No.3 coal seam and No.9 coal seam is 45m. In order to determine water yield property and effect of No.3 coal seam watery goaf, the transient electromagnetic method has been used to detect the area of the No.3 coal seam watery goaf.

3.2. Experimental design
Instrument parameters were determined by data acquisition experiment. A parallel line to the working face was arranged in the corresponding surface area. Length of TEM survey line is 280 m. The dot to survey line is 20m, totally 15 test points. Figure 3 shows the construction layout and detection direction. Based on processing and interpretation of traditional transient electromagnetic data, distribution and boundary of the watery goaf in No.3 coal seam were determined by pseudo seismic imaging system of transient electromagnetic. By comparing with traditional apparent resistivity contour map, effect of two kinds of data processing methods is analyzed.
4. Experimental results and analysis

4.1. Geophysical characteristics and explanation
Regional geophysical characteristics is an important evidence to distinguish abnormal objective, and what is watery goaf. And more, the abnormal body is with characteristic of low resistance and layered distribution. If relative apparent resistivity value is no more than 25Ω·m, then this region can be defined as watery anomaly region, which water content is rich, and with obvious low resistance characteristics. In terms of converted wave field characteristics, the shape of wave field curve reflects to the sharp change of resistivity. According to wave field curve, it is feasible to analyze electrical interface position, as there is obvious amplitude jump curve near it. The more violent for amplitude curve, the more obvious for electrical interface. Therefore, position of the electrical interface is determined by wave amplitude of wave field curve.

4.2. Results explanation
Figure 4 shows the result of traditional transient electromagnetic method. It can be seen from figure 4 that the transient electromagnetic has high lateral resolution and layered distribution character is obvious. There are two obvious low resistivity anomaly areas in the No.3 coal seam. The No.1 anomaly area is distributed in 0 ~ 80m section of surveying point and depth ranges is 30 ~ 53m. The No.2 anomaly area is distributed in 140 ~ 280m section of surveying point and depth ranges are 53 ~ 70m. Due to volume effect of transient electromagnetic method, Actual boundary of watery goaf area can’t reflected accurately by relative low resistivity anomaly range boundary. Therefore, apparent resistivity section diagram can only determine the draft spatial orientation of low resistivity anomaly, and it is difficult to determine actual boundary and influence range of watery goaf in No.3 coal seam.
4.3. Results analysis
Figure 5 shows the result of transient electromagnetic pseudo seismic imaging system. The curve link to each measurement point is converted wave field curve which comes from electromagnetic pseudo seismic process. The two black solid lines are coal seam. The wave field curve shows a relatively strong fluctuation in depth range of 60 to 85m, seen from the figure. The two blue dashed lines are electrical geometry interfaces, which are named for A and B. The most obvious vibration amplitude curve is electrical interface position, which a strong water rich region boundary. Determination of the boundaries of watery goaf improve vertical resolution of the transient electromagnetic method. Lines A and B is actual vertical boundary of water rich goaf.

![Figure 5. Transient electromagnetic pseudo seismic imaging section diagram](image)

Low resistance anomaly depth ranges in the two marked points are from 30 to 70m in transient electromagnetic apparent resistivity section diagram (Figure 4), both are in top of the No. 3 coal seam. It is impossible to determine actual boundaries and influence range of watery goaf by traditional transient electromagnetic data processing, so actual boundaries and impact range of the watery goaf are determined by electrical geometry interfaces A and B (Figure 5). Most of the anomalous areas are located between No.3 coal seam and No.9 coal seam, and depth range is 64 to 85m. Water in goaf enters from the fracture, actual watery goaf boundary is lower than depth of No.3 coal seam. Pseudo seismic processing is more accurate than the traditional transient electromagnetic data processing, validated by actual drilling experiment vertical drilling experiment was arranged from transportation tunnel to the roof. There is a water point in upward 38m. The water point is 7m from No.3 coal seam. Instantaneous water flow is 23m³/h. The drilling results match pseudo seismic imaging results.

5. Conclusions
This paper contributes to numerical analysis of transient electromagnetic with pseudo seismic imaging system. It is concluded that pseudo seismic imaging system is based on wave field condition. Results of the study show that:

1. Pseudo seismic imaging system process is carried out on wave field conversion Seismic wave field is strong in electrical geometry interfaces.
2. The experiment results show that adverse impact of volume effect in transient electromagnetic method is reduced by wave field data processing system.
3. Watery goaf boundary can be accurately detected as two geometric interfaces which are important reference for water hazard prevention. The resolution of transient electromagnetic method can be improved by using pseudo seismic imaging system.
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