The detection and response characteristics of transient electromagnetic signals caused by the deformation and fracture of overlying strata affected by mining of a thick coal seam

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Abstract: The height at which overlying strata fail is an important parameter for the prevention and control of mine water damage. High overlying strata failures during mining of a thick coal seam make testing in mines challenging. Considering the mining conditions for the thick coal seam in Ordos City, Inner Mongolia, China, this work applies ground detection using transient electromagnetics. The response characteristics of transient electromagnetic signals during strata failure were investigated using numerical simulation, and the results of that investigation will provide guidance for on-site exploration. In addition, based on the conditions of the ground and mining face, test wires were distributed within the mining work face area to obtain electromagnetic detection data using large wireframes on the ground to further construct an electrical profile of the coal mining and non-mining areas and explain the characteristics of strata failure. This method succeeded in the practical application and is provided as guidance for strata failure detection for thick coal seam mining.

1. Introduction
Deformation and fractures occur in coal seam roof strata during face mining. The heights at which roof strata fail and the failure patterns are of great concern because those parameters provide vital guidance for mining safety[1-2]. At present, in situ measuring methods, including the borehole flushing fluid observation method, downhole injection and pressure water injection method; the electro-computed tomography (CT) imaging technique; and the borehole television method play a key role in investigations. Those methods observe the characteristics of strata deformations and fractures using various types of testing sensors distributed via downhole drilling. They all demonstrate certain advantages and noticeable disadvantages. The borehole flushing fluid observation method causes huge construction difficulties and costs and is always ineffective due to strata sliding. In addition, the accuracy of the method is influenced by the work experience of construction staff. Regarding the downhole injection and pressure water injection method, an observational tunnel is first constructed parallel to the working face. The length of the tunnel is determined by the location and is usually set to 1/3 of the working face length. Specific water supply pipelines are needed, making project costs high. The electro-CT imaging technique suffers from the characteristic of producing multiple solutions, which requires further study using quantitative modeling and makes the technique inapplicable for real production. The borehole television method can only be applied for wall observations on mines that are fluid-free or that have clear fluid but are casing-free[3]. In addition, the downhole drilling test
system cannot capture the development upper bounds for thick coal seams or large deformations and heights of overlying strata failures. The fixed loop transient electromagnetic method (TEM) for detection based on electrical differences demonstrates the advantages of, for example, large exploration depth, high efficiency, ability to penetrate through high resistance shield layers, rapid data acquisition, sensitivity to abnormal areas, small volume effect and high resolution in vertical and horizontal orientations. Because ground loops are not used for transmission, the use of fixed loop TEM is not confined by surface ground conditions[4-5]. Moreover, strata failure due to coal mining alters the vertical and horizontal patterns of original electrical properties, and the resulting electrical differences provide optimal geophysical conditions for TEM detection technology[6-7]. Therefore, TEM detection technology based on ground conditions demonstrates promising prospects for application to strata failure detection.

However, in recent years, TEM detection technology has been primarily applied to below-mine hydrogeological investigations to provide hydrogeological data for safe production[8]. It has been rarely used for detecting strata failure heights. To guarantee data quality, detection depth and working efficiency, it is important to settle on device type, frame size, transmission frequency and current beforehand so that parameters, including observation method, transmission coil, transmission frequency and sampling frequency, can be determined[9]. Because TEM is largely influenced by its own properties, work experience is required to determine the response characteristics of subsurface geological bodies. In addition, the development of fractures is influenced by a combination of the tensile strength of the key layer, anti-strain ability of the soft-rock layer, height of the free space beneath the rock layer and the advancing distance of the working face[10]. Each of the abovementioned factors produced differently influences the TEM detection results. An improper selection of the distribution plan for the observation system will probably lead to large errors in the detection results and result in severe safety concerns for the coal mining process. Therefore, research studies are required to select optimal distribution plans for observation systems that overlying strata failure heights using TEM.

Considering the mining conditions in the thick coal seam in Ordos City, Inner Mongolia, China, the current work offers a study of ground TEM detection via simulations of a geological model of the overlying strata failure and a discussion of the TEM response characteristics when applied to deformations and fractures due to coal mining. Ground detection was conducted based on the TEM detection results. The measured data were used to determine the height of the overlying strata failure. This study provides guidance for safety assessments of thick coal seam mining under similar conditions and references for investigations on the characteristics of strata failure.

2. Literature Review

TEM was first proposed by a scientist in the former Soviet Union in the 1930s, and the far-field mode of operation was adopted at that time. During the early stages of its application, TEM was confined to metal ore mining. With the development and digitization of devices after 1992, TEM was gradually introduced to and succeeded in investigations in engineering, environmental and catastrophic geological projects, including the detection of coal seam catastrophic areas such as underground goaf fields and collapse columns[11].

As a geophysical detection technology with broad applications and a high economic value, ground TEM has been utilized in research studies for the detection of overlying strata failure heights. To date, research studies have primarily focused on its application to below-mine hydrogeological investigations, for which some experience has been gained. Zhang et al used a TEM device to conduct research on the advanced detection of the height of a fractured zone through which water was flowing and that was caused by overlying strata failure at the goaf field on the working face of a coal seam[12]. Zhou et al applied TEM to measure and analyze the development characteristics of an overlying strata failure at the fully mechanized mining coal face of a coal seam. Their work illustrated the mining pressure characteristics in a coal mining seam close to loose layers and the development height of the two zones[13]. The above mentioned studies applied TEM under the mine. The method used antenna
devices with multi-turn coils, which produced a detection blind spot of approximately 25 meters due to the self and mutual inductances of the coils. Severe interference due to metal was also produced in the tunnel, which greatly influenced the detection results[14]. Therefore, the study of ground TEM detection of overlying strata failure height is very important theoretically and practically.

A large amount of research has been performed on ground TEM detection in abnormal under-mine environments. Li et al worked on a full-view, apparent resistance-based smoke ring inversion technique for TEM and performed one-dimensional inversions on theoretical and observed data[15]. Wang et al compared two numerical simulation methods and discussed parameter selection in their study on electrical source TEM[16]. Xie et al conducted experimental comparisons and analyses on signal-to-noise ratio, stability, and resolution for a uniform loopback device and a figure-8 shaped loopback device used for ground TEM[17]. Han et al. undertook numerical computations, microseismic monitoring, and TEM to analyze the height of overlying strata failure during a regionally stratified, fully mechanized mining process on a coal mining face. They identified the relationship between mining thickness and height of overlying strata failure[18]. Chen & Xue compared the theoretical response characteristics and detection abilities of a loop source and electrical source and then applied the two devices to goaf detection; satisfactory geological results were obtained[19]. Qin constructed a theoretical model for a watered goaf field and investigated the response characteristics of TEM for a typical watered goaf. Their work demonstrates a clear response of TEM on the watered goaf with high resolutions along vertical and horizontal orientations when the detected goaf region satisfied the geophysical conditions, which affirmed the effectiveness of TEM detection for a watered goaf[20]. Qie investigated the goaf field and subsidence area of a coal seam using TEM. An effectiveness test was conducted with known goaf and unmined fields. They eventually identified the goaf field within the mining region[21]. These research studies all applied ground TEM for under-mine goaf detection. The fractured zones produced by the goaf field and overlying strata failures both alter the nearby strata structures and lead to different electrical conditions than the surrounding rocks. Despite this similarity, they also demonstrate negligible differences. Consequently, the experiences of applying ground TEM on goaf detection cannot be directly applied to the height detection of overlying strata failures.

Therefore, to fill the gap in knowledge in current research, we took the mining conditions at the thick coal seam in Ordos City, Inner Mongolia, China, as an example and conducted a further research investigation on the height detection of overlying strata failure by employing ground TEM detection.

3. TEM and the Response Characteristics of Overlying Strata Failure

3.1 Methods and Conditions for the Exploration

TEM is an electromagnetic detection method based on the principle of electromagnetic induction and built in the time domain for use with artificial sources[22-23]. It uses ungrounded or grounded loops to send pulse fields (or a primary field) underground, which excites eddy currents in conductive media. Rather than disappearing during the intervals between two pulses, the eddy currents produce secondary magnetic fields in their vicinity that decay over time. The decay properties of the secondary magnetic fields are determined by the conductivity, scale and burial depth of the media and the shapes and frequencies of the pulse currents. Therefore, the spatial and temporal distribution of the field can be studied by the attenuation characteristics of the secondary field measured by the receiving coil to achieve the purpose of finding underground mineral resources or solving other engineering geological problems.

A goaf field is formed after coal mining destroys the original stress balance in the rock strata. Under the combined effects of gravity and stress from the surrounding rock strata, deformation often occurs at the goaf roof, which results in collapse belts, crevice belts and bending deformation belts. As a result, significant changes occur in the electrical properties of the overlying strata above goafs, providing optimal geophysical conditions for TEM detection of the overlying strata failure.
3.2 Model and Response Characteristics of Overlying Strata Failure

To obtain the TEM detection response characteristics resulting from the deformation and fracture of overlying strata failure, we used ANSYS Maxwell software to simulate models of goaf and unmined fields being filled with water and to analyze the transient electromagnetic signals under different conditions. The model construction process included an analysis of the physical model, selection of unit type, definition of material properties, construction of a geometric simulation model, meshing of model grids, application of boundary conditions, excitation of sources, grid net divisions and parameterizations such as error tolerance and integrating steps. The problem is finally solved by forward simulation.

When simulating transient electromagnetic fields after overlying strata failure, the entire model used a node-based magnetic unit plane 53 to construct a 2-dimensional model, which combines the thick-layer overlying conditions of the detection area and the design of a theoretical geoelectric model (Figure 1). The simulation’s settings were as follows: (1) the diameters of the sending and receiving loops were 100 meters, and the loops were tiled on the ground using overlapping devices. (2) The resistivities of the coal seam, surrounding rock strata and mine water (a relative low resistance body) were set to 1000 Ω·m, 100 Ω·m and 1 Ω·m, respectively. The real domain had open boundary conditions, but the finite element simulation was confined to electromagnetic field computation with a closed boundary; thus, preprocessing of the open boundary conditions was needed for the simulation. This model casts parallel magnetic lines on the outermost air as the boundary condition such that the infinite field state was produced, enabling the finite element simulation. At 500 meters below ground, a coal rake of 20 meters was used as the unmined (non-goaf) background model. After coal mining, overlying strata are destroyed and subside to form a goaf field. To investigate the response characteristics of goafs under different water-filling conditions, models of water-free, half-filled, and fully filled goafs were simulated.

The simulated magnetic line distributions before/after mining under different water-filling conditions are shown in Figure 2. Comparisons among the outcomes of the four situations provided the following results. For the unmined coal seam, the surrounding rock strata remained under the original stress balances, and the strata structure was not damaged. The electromagnetic field was repulsed due to the high resistivity of coal rake and had a weak magnitude. When a goaf forms due to strata failure during coal mining, the response characteristics change at the goaf because it has a repulsive effect when its resistivity is high. When the goaf was half-filled with water, the water at the bottom of the mine was an effective conductor, whereas the air at the top had high resistivity, causing the magnetic lines to be influenced by gravitational forces at the bottom and repulsive forces at the upper level. When the goaf was fully filled with water, the magnetic lines changed due to low resistance and were significantly influenced by gravitational forces. The goaf’s height, location and
water-fill condition could be determined by the distribution of magnetic lines. Therefore, it was feasible to determine the response characteristics of the overlying strata failure during mining using TEM.

(a) unmined  
(b) not filled with water  
(c) half filled with water  
(d) filled with water  

Figure 2. Distributions of magnetic lines under different water fill conditions.

4. In situ Investigation and Analysis

4.1 Data Acquisition

Through the comparison of different parameters and the investigation of influencing factors, we can further get effective application results, and we need to pay attention to several aspects for improving the quality of field exploration. First, test the wireframe and cable selection. Within a certain range of side length, the anomalous amplitude of the geological body increases linearly with the increase of the side length. Second, the size of the topographic relief in the survey area will also affect the data collected. In addition, there will be some differences in the response characteristics of abnormal bodies detected under different inclined strata. Third, on-site interference conditions investigation. Electromagnetic noise mainly from the outside, high voltage wires around the test site and other electromagnetic interference survey to reduce the sensitivity and observational capabilities of the instrument. Fourth is the data processing needs to be based on the characteristics of the acquisition of induced electromotive force pre-processing, calculation of resistivity can be adjusted according to the test medium conditions coefficient. Fifth is the electrical conductivity of the geological body, depth and geometry parameters. The amplitude of anomaly is related to the electrical and geometric parameters of the geological body. The better conductivity of the geological body, the greater of
geometric parameters, and the abnormal amplitude is high, the method of detection of the target body is strong.

Figure 3. Layout of surface surveying line.

An experimental region was designed that corresponded to the simulation experiments. To obtain data representative of coal seam roof damage, four experimental lines were distributed over the goaf and unmined fields in the test area, along the rearward direction of the working face. The experimental lines were formed into a # shape and are denoted as Lines 1#, 2#, 3#, and 4#. Lines 1# and 3# had shorter sides of 100 meters, and Lines 2# and 4# had longer sides of 200 meters. Lines 2# and 4# were parallel to the rearward direction and were separated by 150 meters, and they crossed over the goaf and unmined working face. Lines 1# and 3# were located above the unmined and goaf fields, respectively. For the in situ investigation, a test plan was developed due to the depth of the area, with the principle of altering one factor at a time to guarantee effective data acquisition and raw data quality. The experimental setup, including the layout of the observation system and establishment of the receiving conditions, guaranteed effective TEM data acquisition. An experiment to determine the sizes of the sending/receiving loops was undertaken, and lengths ranging from 10 to 100 meters were considered. Eventually, the large side length with overlapping loops was selected for the small-step construction program. Field test using MSD-1 transient electromagnetic instrument. The lengths of the sides of the receiving loop were 100 meters, with 10 turns, and the sending loop also had side lengths of 100 meters but with 20 turns. The spacing between measurement points was 5 meters. 8.3Hz is chosen as the data acquisition frequency and the emission current is 15A. In order to obtain reliable signals, multiple stacking techniques are used, and the number of stacking is 256 times. Figure 3 shows a sketch of the field survey’s layout. The data obtained following this plan were of high quality. Figure 4 shows a picture of the field transient wire frame arrangement.
4.2 Geoelectric Profile Interpretation

Data analysis was performed using self-complied software [24-25]. The primary processes included data editing, coordinate construction, data pre-processing and correction, computation and visualization of apparent resistivities, integrated control of geological information, qualitative and semi-quantitative interpretations of apparent resistivity anomalies and identification of abnormal regions. Among them, the inversion scheme is based on the whole area apparent resistivity of smoke circle inversion technology for data processing. Profiles of apparent resistivity for the different experimental lines were obtained via the abovementioned procedure, and the electrical anomalies at the corresponding locations were used to analyze the strata characteristics.

The analysis focuses on a comparison of the application of ground TEM on the goaf and unmined fields, discusses the resistivity anomaly during underground strata deformation and fracture process and determines the overlying strata failure. Figure 5 is a pseudosection map view of the apparent resistivity of four lines in the measuring area, in which the test direction of 2# and 4# lines is moved from the direction of the non mining area to the goaf, and the 1# line is arranged above the non mining area, and the 3# line is arranged above the goaf. Through the test results, it is found that the electrical characteristics of the rock layers above the working face in the goaf and the non mining strata have been changed obviously, and the apparent resistivity of the inner layer structure in the area of the goaf is obviously increased, and the better comparison results can be obtained through the two parallel lines of 2# and 4#. The overall apparent resistivity of the lower strata in the area of the length of the line 0-100m in the mining area is small. Without coal mining, the strata within the unmined field were not damaged by the disturbance. The rock strata at the working face were the goaf field, the electric characteristics of which changed significantly. Between 100 to 200 meters along the experimental line, at depths of -450 to -550 meters, the apparent resistivity increased significantly to 3000 Ω·m, three times that of the apparent resistivity at the unmined field (1000 Ω·m), and demonstrated a separation into multiple belts. The results obtained from 2# and 4# measurements show that they have good consistency in the test results, and the test results are more accurate. Comparing the 1# and 3# lines, it is found that the apparent resistivity of the rock mass in the uncollected area is low, and the background resistivity under the undisturbed condition is basically 500 Ω·m. The result map of the 3# line above the goaf is found to be affected by the coal seam mining and the apparent resistivity value of the rock mass within the range of -450 - 550m. The whole is 3000 Ω·m. The magnitude and distribution of resistivity indicates that coal mining causes significant changes in overlying strata structure and results in significantly high apparent resistivities when compared with unmined fields, findings that can help guide integrated interpretation and determination.
In order to more accurately determine the results of this transient electromagnetic field test, the values of apparent resistivity on different depths of the 1# and 3# lines are extracted and the average processing is carried out. In addition, the 2# and 4# lines respectively extract and measure the electrical data above the untaken area in the range of 0-100m and the electrical data above the gob in the range of 100-200m. Finally, an average apparent resistivity curve at different depth positions as shown in Figure 6 is obtained. It can be seen that the apparent resistivity of the rock strata above the non mining area is around 500 Ω·m, and the average apparent resistivity of the depth is below 1000 Ω·m in the range of 0-450 m, while the average apparent resistivity in the range from -450 m to -550 m increases rapidly to 2000 - 3000 Ω·m indicates that the rock mass structure is affected by mining failure in this depth.
A comprehensive analysis of the electric profile characteristics for the different experimental lines illustrated that the goaf fields experienced stratal deformation and fracture and demonstrated significant differences in comparison with the unmined field. Strata resistivity increased at the fractured zone and thus can be used to interpret and determine strata deformation and fracture during mining. A comprehensive comparison found that strata 85 meters above the coal seam roof were significantly influenced by the 6-layer coal mining. That influence can reach 105 meters above the roof at its highest. The failure height of the overlying surrounding rock obtained by the ground test is basically consistent with the result of drilling and coring verification.

5. Conclusions

1) Deformation and fracture occur in overlying strata during coal mining. The electromagnetic fields in the region of damage experience significant responses. The fracture zone through which water flows demonstrates high resistivity, and the resistivity structure is different after mining; the considerable difference in resistivity meets the criteria for determining strata deformation and fracture.

2) Due to the topography, the optimal loop for data acquisition was a rectangular frame with side lengths of approximately 100 meters and large numbers of rounds. Low resistivity copper coils are optimal for collecting accurate data. The distribution of experimental lines can be designed along the strike and dip of the working face so that the geoelectric profile can extend across the goaf and unmined fields to allow comparison and analysis of the characteristics of the geoelectric medium. The deformation and fracture of overlying strata during thick coal seam mining in West Inner Mongolia demonstrated typical characteristics. The resistivity above the goaf field was three times that above the unmined field, which can be used to determine the height of the overlying strata failure.

3) As a consequence of technology limitations, further study is needed to apply TEM to detecting the response characteristics of strata deformation. More experience with the theorem of depth computing is needed for research on regional characteristics. This method can provide guidance for similar research studies.

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