Fine detection of mine collapse column by anti-explosive ground penetrating radar

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Abstract

This work discussed the technique for fine detection of mine collapse column by anti-explosive ground penetrating radar (GPR) and its feasibility. In stage of theoretical research, numerical forward modelling was used to study the response characteristics of collapse column on radar profile. In actual exploration, the spatial distribution pattern of collapse column was accurately stored by installing complex environment observing system in the pit. In processing and explanation, the disturbance types of mine were comprehensively analysed, and various measures were taken in the suppression of interference signals to obtain better exploration effects. The study showed that fine detection of collapse column can be realized by anti-explosive ground penetrating radar under the complex conditions in the pit.

Keywords: Anti-explosive ground penetrating radar (GPR), collapse column, fine detection

1 Introduction

Mine collapse column is one of the key problems for mine production [1]. Collapse column is generally formed by sinking of overlying rock. Such sinking results from the cavity, which is caused by the underground water corrosion of soluble rock underlain in coal measure strata. If the collapse column without solid filling is connected with runoff belt in aquifer of mining area with rich underground water, water burst and even inundation may possibly occur when work surface is directly exposed or gets close [2].

The detection of collapse column in the pit is mainly by drilling and geophysical prospecting. Drilling is perceptual but limited by the layout condition of drill hole, so it cannot completely reflect the distribution of collapse column [3]. With advantages of area detection, geophysical prospecting is widely applied to obtain obvious geological effects. The main methods include seismic detection, direct current electric method, transient electromagnetic, and pit penetration. However, it is difficult to arrange effective observing system in the complex and narrow space of mine when using seismic detection, direct current electric method, etc. Therefore, the exploration completeness and accuracy of collapse column will be affected [4, 5]. Moreover, geophysical prospecting is also limited by the gas environment in the pit. Equipment not reaching anti-explosive safety grade cannot be used in the pit.

Anti-explosive GPR can safely work in the pit. With small volume, light weight, and collection method of point detection or continuous detection, it can flexibly arrange the survey lines according to specific environment. Moreover, the screen-type design can effectively shield interference in the pit [6]. Meanwhile, featured with high resolution and efficiency of common GPR, it can finely detect the spatial distribution of collapse column [7]. This work mainly introduced technology methods and application effects about the detection of mine collapse column by anti-explosive GPR.

2 Theory of GPR

The concept of GPR was proposed by Germany Letmbatch and Lowy in 1910 at the earliest. It can detect the target by emitting high-frequency impulse electromagnetic (in frequency scope of 106~109Hz) to the medium [8]. Mediums with different relative dielectric constants have different reflections of electromagnetic wave, and its factor r can be expressed as follows:

$$r = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}, \quad (1)$$

where ε_1 and ε_2 represent relative dielectric constants of medium 1 and medium 2, respectively. The distribution scope of the constant is 1 (air) < ε <81 (water). The larger the difference between relative dielectric constants, the stronger the reflection energy of electromagnetic wave will be.

Figure 1 show the principle that the GPR emits high-frequency electromagnetic pulse to the medium. The travel time of impulse wave can be expressed as follows:

$$t = \frac{4z^2 + x^2}{v}, \quad (2)$$

where, t is the two way travel time of electromagnetic wave, z is reflector depth, v is the wave speed in underground medium, and x is the distance between transmitting antenna and receiving antenna (distance between receiver and transmitter).

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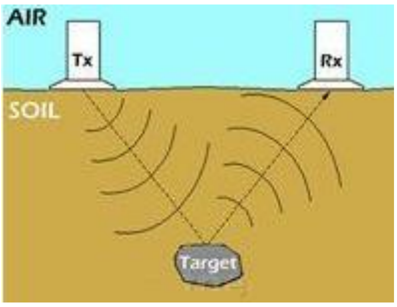


FIGURE 1 Schematic diagram for the principle of ground penetrating radar (GPR) detection

This study used ZRT intrinsically safe GPR developed by China University of Mining and Technology (Beijing). It can be safely used in the gas environment of pit. With central frequency of 180MHz, this radar antenna adopted screened antenna "integrating with receiving and transmission". Compared to the exploration depth z, the distance between receiver and transmitter can be deemed as $x \approx 0$ for the close distance between receiving antenna and transmission antenna. Therefore, the two-way travel time of impulse can be expressed as follows:

$$t = \frac{2z}{v}, \tag{3}$$

where wave speed v is related to the relative dielectric constant of medium. The larger the relative dielectric constant of medium, the slower the radar wave will transmit in the medium. The relational expression between both is as follows:

$$v = \frac{c}{\sqrt{\varepsilon}}. \tag{4}$$

When the speed of electromagnetic wave in medium v is known, the depth of reflection target z can be obtained by Equation (3) according to the measured accurate time t.

When transmitting in the medium, the properties of electromagnetic wave, including amplitude, phase, and waveform will change with the electromagnetic property and geometrical morphology of medium. Therefore, the structure and nature of medium can be deduced according to the received data about travel time, amplitude, and waveform of radar wave. Radar detection reflects the measured medium with profile, which is the record for the form of reflection wave. The positive and negative energy are represented with black and black, or the gray and color scale, respectively. Compared with other geophysical prospecting, GRP can more intuitively reflect the detection results, and can make preliminary reference and judgment at site.

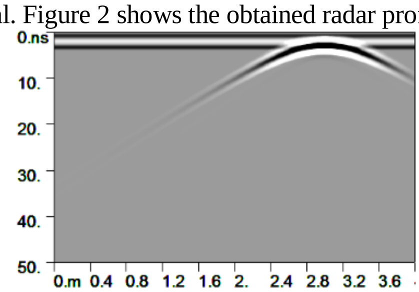
3 Geophysical characteristics of collapse column

Collapse column of coal measures is generally caused by the continuous upward collapse in large-span solution cavity of soluble rock series underlies in coal measures. There is a large difference between electrical property of coal measures and that of the rock mass in collapse column in coal measure strata. Therefore, the radar reflection wave with strong energy can be formed in the boundary of collapse column. In general, the development of collapse can be divided into 4 stages: early development stage, strong development stage, decline stage, and dead stage [9]. For the collapse column in different development stages, the filling degree of inner cement, water transmissibility and abundance, the damage status of surrounding rock distribution, and the associate structure are all completely different. Therefore, their geophysical characteristics are different in electric property.

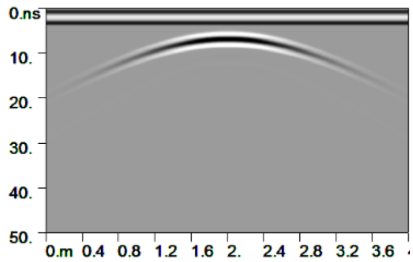
In general, collapse column is elliptic cylinder or oblate cylinder in space, and irregular cylinder in profile [9]. The dielectric constant of collapse column is obviously different with that of surrounding rock stratum and coal bed. Moreover, with water or air in marginal area, the difference of dielectric constant and conductivity may surge to enhance the reflection energy of radar signal. Although the reflection energy is strong, the distribution of wave group is in disorder because of the complex binding form between collapse column and its margin and surrounding rock [10].

In order to study the radar respond characteristics of collapse column, finite difference time domain was adopted to simulate the radar wave generation and the transmission in coal and rock medium.

Firstly, a collapse column with elliptic cross section was designed, and its long axis was 3.2 meters and short axis 1.8 meters in horizontal. Then, the collapse column was detected by simulating GPR penetrating the lateral wall of lane with survey lines parallel to long and short axis were laid in horizontal. Figure 2 shows the obtained radar profile.



a) Simulated effects of radar profile when survey line parallel to the short axis of collapse column in horizontal



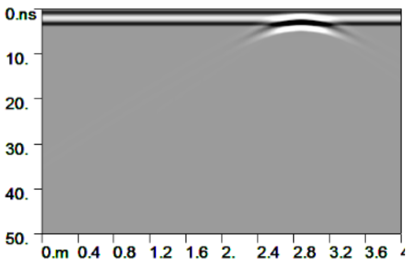
b) Simulated effects of radar profile when survey line parallel to the long axis of collapse column in horizontal

FIGURE 2 Simulated radar profile of collapse column in horizontal section

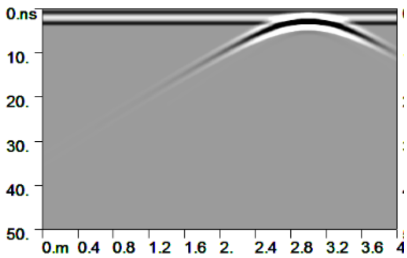
In simulated profile, the response of detected collapse column parallel to long axis should be obviously wider than that to short axis. Therefore, the distribution for the long and short axis of collapse column can be differentiated according to this characteristic.

In addition, the contrast simulation was conducted for the change of collapse column conductivity and dielectric constant caused by different moisture contents. Water may increase the conductivity and dielectric constant of collapse column [11]. Figure 3 shows two respond profiles of collapse column with different conductivities and dielectric constants. In this figure, Figure 3a shows the non-aqueous condition that the conductivity is 10-7S/m and dielectric constant is 7. Figure 3b shows the aqueous condition that the collapse conductivity is 10-2S/m and dielectric constant is 14. According to the radar profile, the response energy of aqueous collapse column is obviously higher than that of non-aqueous collapse column [12].

Furthermore, the contrastively simulations detection of collapse column has been used according to the change of conductivity and permittivity of collapse column for different moisture content as well. The conductivity and permittivity of collapse column will increase because of the water in medium, so in the radar response profile of collapse column of two group different conductivity and permittivity in the Figure 3, Figure 3a shows the conductivity of collapse column is 10-7S/m, and the permittivity is under no water circumstance value 7. Figure 3b shows there contain water in the medium, the conductivity of collapse column is 10-2S/m, the permittivity of it is 14. The response energy of collapse column of containing water is significantly higher than collapse column of no water according to the radar profile [13].



a) Profile of non-aqueous collapse column



b) Profile of aqueous collapse column

FIGURE 3 Comparison chart for simulated profiles of collapse column with different aqueous conditions

According to the forward modelling radar profile, characteristics of collapse column were judged in aspects of layout position, form, water containing, etc.

4 Actual detection

There is a collapse column with 73m long axis and 45m short axis between main rail haulage roadway and air return roadway in the primary mineable coal bed in Shanxi Province. As shown in Figure 4, the exploration of air return roadway keeps away from this collapse column by bypassing up to the mountain. Coal faces 8102 and 8103 are located in the north to collapse column.

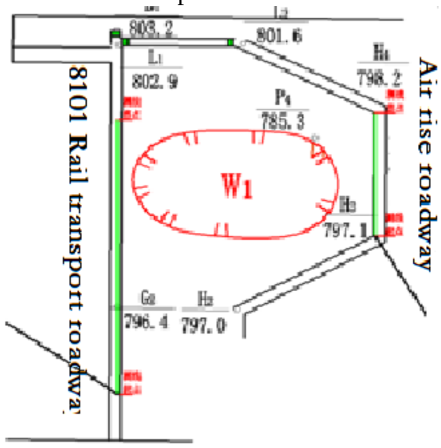


FIGURE 4 Schematic diagram for survey lines of 8101 rail haulage roadway

4.1 DATA COLLECTION

This mine is a newly-established shaft without detailed geological data, so two main radar survey lines were laid for the lateral walls of two roadways neighboring to collapse column after knowing the surrounding rock in transportation roadway and air return way. As shown in Figure 5, two survey lines of lateral walls along crossheading of rail are 110m long, while those along air return roadway are 50m long. As shown in Figure 6, two short survey lines were set in lateral wall and head on work faces 8103 and 8102, which were 18m and 19m long.

This study used ZRT intrinsically safe GPR developed by China University of Mining and Technology (Beijing). Its central frequency is 180MHz. In order to reach 30m detection depth, the time window for collection was set as 700ns, and the sampling point number as 1024. Detection was conducted by continuous collection for 4 times.

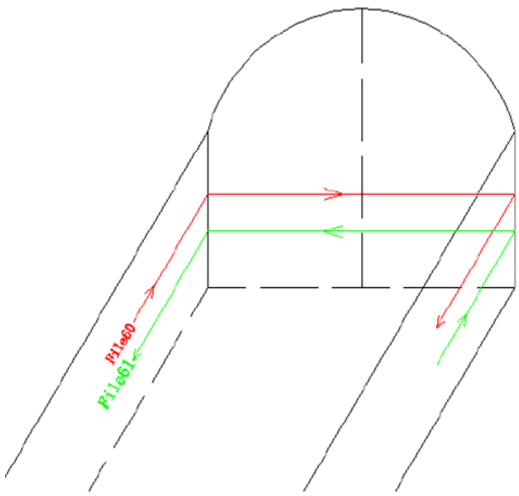


FIGURE 5 Schematic diagram of radar survey line layout

4.2 DATA PROCESSING

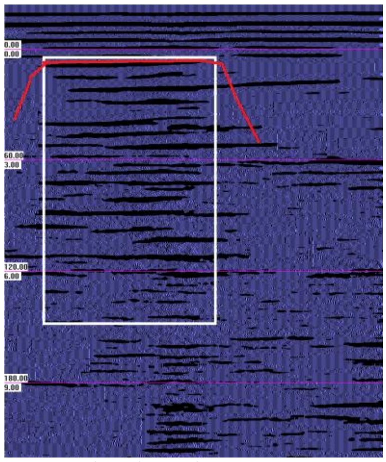
Self-developed GR processing and explaining software was adopted in the processing of collected data. In regular processing, gain adjustment, one-dimensional filtering, FK filtering, and wavelet transform were used. In addition, signal-to-noise ratio can truly reflect the change of detected medium and ensure data quality [14].

4.3 EXPLANATION OF REGULAR DATA

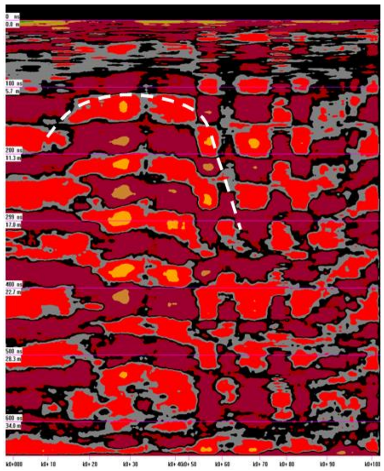
GPR detects anomalous body with the variance of electromagnetic property. GPR analyses the variance between collapse column boundary and surrounding mediums and the reflection of collapse column on radar profile according to the geological data. Then, the distribution scope of collapse column can be determined. The time profile of radar is mainly identified according to the changes of reflection energy on different time axis because there is a large difference of electric property between collapse column boundary and surrounding rock mass. Non-aqueous collapse column may generate disordered reflection waves which are superposed after multiple reflections under the obvious reflecting layer. If the collapse column is aqueous and water-transporting, however, the radar wave energy may be adsorbed and reduced under the reflecting layer of strong margin, while the reflection energy layer may be enhanced. In addition, the depth of abnormal position can be judged by reading the reflection time of abnormality distributing on radar profile according to the relevance between transmission speed of electronic wave in medium and relative dielectric constant of medium [15].

1) Figure 7 shows the detection results of radar in the rail haulage roadway. In the profile detected in rail haulage roadway, there is an obvious lithological variance belt during 100ns-250ns. According to geological data, it can be regarded as the boundary affected by collapse column. The surrounding rocks of haulage roadway are mainly mud rock of Taiyuan Fm in carboniferous system, and their relative dielectric constant is in scope of 8-15. Therefore, the boundary affected by collapse column can be estimated according to the formula of radar wave speed and the equation of time interval during radar wave transmission. This boundary is about 5-12m away from the lateral wall of rail haulage roadway, and its form distribution in plane conforms to the circular arc of collapse column boundary. Moreover, the reflection clutters are still disordered in the lower part of time axis on profile, and the energy does not generate strong absorption and reduction. Therefore, it can be determined that this collapse column is not water-transporting.

2) Figure 7 shows the radar detection results of air return roadway up to the mountain. The air return roadway up to the mountain is located in the east to collapse column. In the radar time profile, strong reflection energy layer can be seen during 120ns-260ns. Therefore, it can be determined that this roadway is in the boundary affected by collapse column. The roadway is about 7-15 meters away from the lateral wall, and has the boundary shape of collapse column. However, the energy on and below reflecting layer obviously enhances than the profile detected in rail haulage roadway before. According to the analysis on radar response characteristics in forward simulation, the moisture content in the collapse column near the air return roadway is higher than that near the rail haulage roadway.



a) Profile of waveform variable area

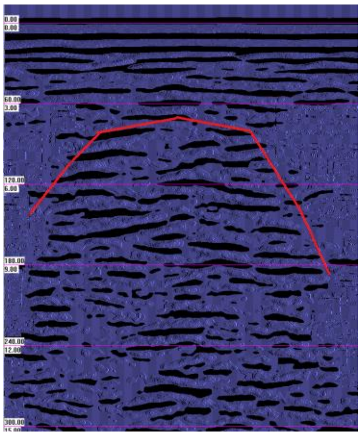


b) Colorful profile

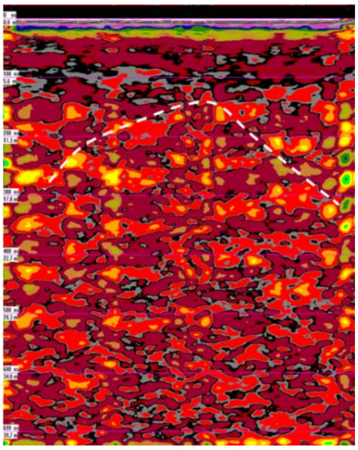
FIGURE 6 Radar detection profile of collapse column in rail haulage roadway

According to the comprehensive analysis on the radar profile of two survey lines, this collapse column has moisture change in partial region, but does not been connected. Therefore, it can be determined that the collapse column is not water-transporting in horizontal.

3) Radar detection results in other regions are as follows. There is anchor network, steel-frame shed, and support plank in the most detection position of lateral wall and frontal plane on 8103 work face. Therefore, the coupling with surrounding rock is bad, and the interference signal is strong during radar detection, which affects the detection results to some extent. After a series of signal processing, the signal-to-noise ratio increases. However, there is no obvious reflecting layer on radar profile when detecting the frontal plane, while an obvious energy reflecting variance belt is found when detecting the lateral wall (See Figure 8). It can be judged as the reflection caused by collapse column. However, the survey line at this section is short, so the judgment of position distribution may have large error.

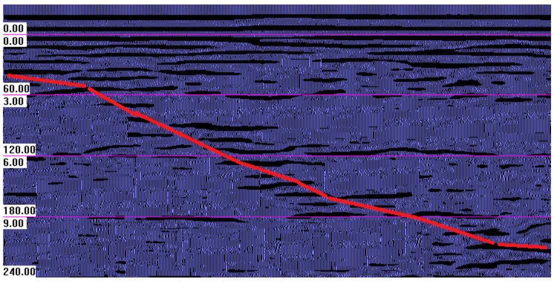


a) Profile of waveform variable area

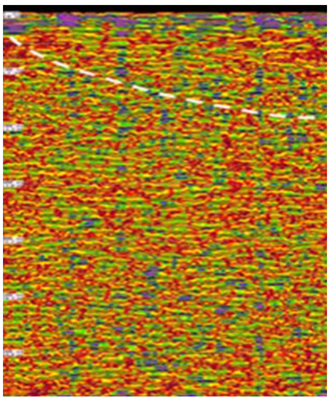


b) Colorful profile

FIGURE 7 Radar detection profile of collapse column in air return roadway up to the mountain



a) Profile of waveform variable area



b) Colorful profile

FIGURE 8 Schematic diagram of reflecting energy variance belt in lateral wall on work face

According to all above results, the basic form of collapse column distribution is determined by radar detection on the horizontal plane surrounded by the lateral wall, rail haulage roadway, and air return roadway up to the mountain on 8103 work face. In order to verify the detection accuracy of GRP in the pit, the explanation achievements are compared with original geological data of tunnel prospecting and drilling. It can be found that the collapse column conforms to the distribution in horizontal. In Figure 9, the area circled with green imaginary line is the distribution scope of collapse column in horizontal determined according to radar profile. And the area circled with red active line is the distribution scope of collapse column provided in the geological data of this mine. These two areas have high superposition if the survey lines are laid long enough to ensure the detection accuracy.

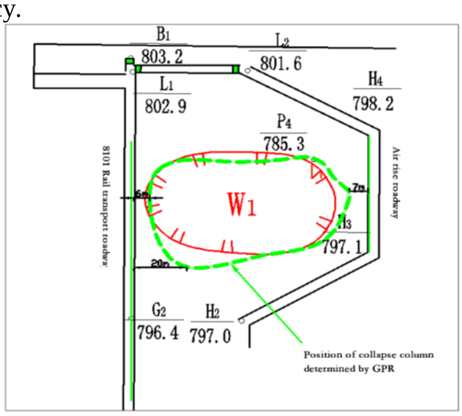


FIGURE 9 Comparison diagram between collapse column positions in radar detection and geological data

5 Conclusions

Theoretical analysis and actual engineering study are conducted on the detection of collapse column in the pit with anti-explosive GPR. Scientific and rational layout of survey lines and utilization of limited space in complex mine environment are significant to obtain radar data with high signal-to-noise ratio.

With rational and sufficient layout of survey lines, the anti-explosive GPR can reflect the spatial distribution of collapse column and moisture and water-transporting of collapse column. Moreover, effective layout of survey lines can be used to accurately determine the distribution scope of collapse column in horizontal.

Practices show that anti-explosive GPR has advantages of high resolution, flexibility, lossless, anti-interference, etc. when detecting the collapse column in the pit. Therefore, it is incomparably advantageous to other geophysical methods. Except collapse column detection, anti-explosive GPR in the pit can also be applied to safety detection of other disaster sources in the mine pit.

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