The application of GPR and EH4 in the exploration of iron mine goaf

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Abstract. To study the distribution of goaf at Heiwang iron mine, the iron ore goaf detection was given prior to with GPR method and the EH4 method was used to supplement in the goaf of the deeper and larger areas. The high resolution radar time section and EL line resistivity inversion section were determined. The reliable geological interpretation was studied. It was shown that there existed suspected large mined-out area within the pile number of 0~80m of buried deep below 50m. There was a big volume of mined-out area within the pile number of -30~60m of buried deep below 50m. The high resistivity distribution region of the elevation of within the pile number of -30~140m of buried deep below 120m was inferred to be an unmineralized orite layer. It was proved that the two methods could complement each other and improved the accuracy of the evaluation of goaf.

1. Introduction
The goaf was one of the important reasons for mining safety accidents. It was of great significance for the management work in the later period to accurately detect the goaf and grasped the spatial distribution of the goaf. Liu et al.[1] analyzed the key factors affecting the precision detection of goaf. Zhang et al.[2] studied the exploration and comprehensive treatment of goaf, and put forward the idea of exploration, numerical analysis and integrated governance. Huang et al.[3] introduced the application of GPR in goaf. Wang[4] introduced the application of EH4 electromagnetic imaging system in the boundary exploration of goaf. Li et al.[5] introduced the application of distributed high density electrical method to the detection of shallow goaf. Yan et al.[6] introduced the application of high frequency electromagnetic detection method in goaf. Song et al.[7] studied the stability of goaf group in metal mines based on precision detection. In this paper, the application of GPR detection method and EH4 were introduced to provide the decision-making basis and reference for the detection of goaf.

2. The choice of detection methods in goaf
2.1. The profile of measurement area
The exploration area is located on the west side of the Heiwang iron ore mine in Shandong province. The deposit is a medium low temperature hot filling type iron ore. The ore formation is complex, the distribution of ore body is scattered and the grade is changed greatly. Illegal mining and beneficiation
activities are very serious, which left a large number of non-standard sizes, shapes of empty area. 35 GPR lines are arranged in geophysical prospecting area according to the known geological data, mission requirements, and considering the situation of surface. The dot spacing of measured line was 1m. Two EH4 exploration lines are set according to the result of radar detection. The dot spacing of EH4 exploration lines was 10–20m. One detection line and one EH4 prospecting line were selected for analysis.

2.2. The selection of geophysical methods
The topography and surface conditions of the detection area are complex, some areas are the bedrock area, some areas are slope platforms and some areas are rock fragments after blasting. Most of the surface hardness is not easy to pave electrode. The width of the slope platform was too narrow to satisfy the electromagnetic exploration method. And the GPR had non-destructive and rapid advantages, which was better suited to work under bad conditions than in the case of electric prospecting. Mined-out areas were mostly not water cavities, and the bedrock was high resistance body. Its volume was relatively small. The electrical method was not ideal. There may be more apparent only in large scope of the underground mined-out area. The detection of iron ore mining was mainly based on the method of GPR, which was supported by the EH4 method in the region with deep burial and wide scope.

2.3. The principle of GPR detection method
Geological radar was a geophysical exploration technique which uses high frequency electromagnetic waves to detect underground geological structures and features. Electromagnetic wave propagation in a particular medium speed was constant. The buried depth of abnormal medium $H$ was calculated by the geological radar electromagnetic wave propagation time $\Delta T$. [8]

$$H = V \frac{\Delta T}{2}$$

Where $V$ is the propagation speed of electromagnetic waves in the medium.

The amplitude of the echo signal was proportional to the reflection system, and in the low dissipation medium as the main displacement current the reflection coefficient can be expressed in equation(2).

$$r = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}}$$

Where $\varepsilon$ is the relative dielectric constant. And the dielectric constant was different for different media.

The intensity of the reflected signal depended on the electrical difference of the upper and lower medium. The greater the difference of the electrical difference was, the stronger the reflected signal was. The penetration depth of radar waves depended mainly on the electricity and frequency of the underground medium. The higher the conductivity was, the lower the penetration depth was. The higher the frequency was, the lower the penetration depth was.

2.4. The basic principle of EH4 method
The changing electromagnetic fields were propagated in the form of waves, and the electromagnetic waves of different frequencies had different penetration depth. Therefore, the analysis of the electromagnetic fields of different frequencies observed on the surface of the earth could obtain the information of the conductivity of underground strata. The EH4 electromagnetic imaging system was based on the electromagnetic wave propagation theory and Maxwell's equations, and the electric field and magnetic field of the horizontal electric dipole source in non-uniform and semi-space were derived. For non-uniform media, the calculation formula of the earth electromagnetic sounding was calculated[9]

$$\rho_\theta = 0.2T |Z_\theta|^2$$

(3)
Where $T$-The vibration period of electromagnetic field. $Z_{ij} = E_i/H_j$ is the complex impedance of $ij$ plane.

$\rho_{ij}$ - apparent resistivity of $I, j$ plane.

In frequency domain, the relationship between each component of the earth's electromagnetic field could be expressed as

$$
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix} =
\begin{pmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{pmatrix}
\begin{pmatrix}
H_x \\
H_y
\end{pmatrix}
$$

The electromagnetic field components were observed results and the second order matrix was complex impedance tensor. The observational data contained complex noises. In order to obtain more accurate impedance elements, a large amount of data was collected. Then the best estimate was calculated based on the least squares principle.

3. Information interpretation and detection results

3.1. Selection of acquisition parameter

1) Selection of acquisition parameter of GPR

Through field observation test, acquisition parameters are as follows:

Frequency of measuring antenna is 20MHz; spot measurement, the distance among the points is 1m; the distance between transmitting antenna and receiving antenna is 3m; the number of sweeps is 128 times; automatic gain control; the window of sampling time is 1000~1200ns; the sampling points are 1024.

2) Selection of acquisition parameter of EH4

Measuring frequency band is $10 \sim 1000$Hz; data superposition times are sixteen; notch filter; according to the actual strength of the electromagnetic field signal, the gain ranges from -1 to 80dB; distance of electrode is 10m; considering the actual situation, the space between receiver of this detection is from 1500 ~ 2000 m.

The photos of field data acquisition of GPR and EH4 are shown in Figure 1.

![Figure 1. Field data collection.](image)

3.2. The data interpretation of GPR detection

3.2.1 Method of data interpretation

(1) velocity analysis

The measured GPR time section in the end of line is shown in Figure 2, the bottom of the pile number of 56 ~ 68m is the cavity that is visible to the naked eye, the actual measured depth is 11.3m, reflection coefficient of radar wave is positive, because of the launch phase wavelet of radar instrument is negative, so reflection wave of the cavity goaf is the negative phase. It can be seen from Fig.2, the reflected wave energy mined-out area is strong in the area of 56~68m, round-trip time of
peak phase is 198.35ns, consider the transceiver distance of antenna is 3m, Thus we can calculate the radar’s wave velocity of the bedrock which is 0.115m/ns, and the relative dielectric constant is 6.81.

(2) method of interpretation of radar profile

The measured time section of GPR is shown in Figure 3, it clearly shows the distribution of underground backfill crushed stone, bedrock interface and the goaf. Along the direction of the line, the reflected wave of backfill crushed stone and bedrock interface can be continuously tracked. There are eight obvious mined-out area distributed in the area of 0~152m, most of them are embodied in the form of hyperbolic curve.

![Figure 2. The measured GPR time section in the end of line.](image)

![Figure 3. The measured time section of GPR.](image)

3.2.2 The data interpretation of GPR detection

The interpretation of the radar profile was shown in Figure 4, which clearly showed the distribution of underground backfill gravel and bedrock interface and goaf. The reflection wave of the backfill and bedrock interface could be traced continuously along the measured line direction. There were 10 obvious goaf regions in 0~248.24m. Most of goaf region were in hyperbolic shape.

The top interface of the goaf was injected into the cavity from the bedrock interface and the reflection coefficient was positive and the negative phase was shown in black. The base plate was the radar wave from the cavity into the bedrock, and the reflection coefficient was negative.
The expression is positive phase in white. The top interface of the goaf was calculated according to the velocity of bedrock, while the height of the goaf should be calculated according to the velocity of the reflectance of the interface in the air. The interpretation results of L₁ detecting line were shown in Table 1.

![Figure 4. Time profile of the geodesy radar of L₁ detecting line.](image)

| The distance of detecting line /m | The time of the double–path reflected from the top of the goaf /ns | The time of the double–path reflected from the bottom of the goaf /ns | The depth of top interface of goaf /m | The height of goaf /m | Character description |
|---------------------------------|---------------------------------------------------------------|---------------------------------------------------------------|----------------------------------|------------------|---------------------|
| 0~4                             | 366.12                                                        | 566.06                                                        | 20.21                            | 29.99            | Cavity              |
| 21.8~28.0                       | 283.30                                                        | 413.13                                                        | 15.36                            | 19.47            | The gravel at bottom |
| 52~56                           | 283.53                                                        | 320.15                                                        | 15.42                            | 5.50             | Cavity              |
| 64.2~68.1                       | 318.18                                                        | 427.69                                                        | 13.24                            | 16.43            | The gravel at bottom |
| 98.1~102.3                      | 331.12                                                        | 448.23                                                        | 18.11                            | 17.57            | Cavity              |
| 136.2~142.5                     | 227.51                                                        | 330.35                                                        | 13.12                            | 15.43            | Cavity              |
| 154.3~166.0                     | 326.21                                                        | 520.54                                                        | 18.21                            | 29.15            | Cavity              |
| 186.21~198.13                   | 305.01                                                        | 410.09                                                        | 17.12                            | 15.76            | Cavity              |
| 216.03~222.03                   | 280.95                                                        | 480.03                                                        | 16.12                            | 29.86            | Cavity              |
| 244.06~248.24                   | 260.25                                                        | 392.16                                                        | 14.23                            | 19.79            | Cavity              |

3.3 The data interpretation of EH4

As an auxiliary exploration method, the earth electromagnetic prospecting line of EH4 was designed, which was designed according to the radar detection results, and controlled whether there was a wide area of goaf in the deep part. The inversion resistivity profile of EL line was shown in Figure 5. The ground elevation of the line was 200 ~ 220m.

![Figure 5. The inversion resistivity profile of EL line.](image)

(1) The segment formation resistivity was higher, which led to the large blind area (10~40m) of the detection, so that the 40m existed in light of the mined-out area could not be detected out. In fact,
most of the mined-out area is distributed in the range of 0~40 m depth. That should not be in the whole detection area to carry out the EH4 magnetotelluric sounding method to detect mined-out area of work. The key area for deep or radar display (below 40m) was a wide range of goaf anomaly areas to supplement exploration.

(2) The change of resistivity more reflected the grey degree of mineralization from resistivity distribution. The resistivity of low degree of mineralization or mineralized rock is bigger than the resistivity of high degree of mineralization in bedrock. This covered the abnormal changes of mined-out area. The resistivity distribution of the measured line showed that the resistivity of the south to the north bedrock was gradually decreased, thus the mineralization degree of the south to the north bedrock was gradually increased.

(3) There existed suspected large mined-out area at the pile number 0~80m, and the depth is below 50m according to Line L1 detection by radar. In order to further clarify the deep area, the electromagnetic line EL was arranged by EH4 for the safety of local residents. There existed anomaly area of high resistivity at the elevation of 140-160m in the range of 30~60m pile. The abnormal area was caused by underground mined-out area in combination with radar L1 line detection results. Thus there was a big volume of mined-out area at the pile of 30~60m below 50 m of buried depth. The high resistivity distribution region of the elevation of 120m depth, at 30~140m pile segment was inferred to be an unmineralized orite layer.

4. Conclusions
The iron ore goaf detection was given prior to with GPR method. The EH4 method was used to supplement in the goaf of the deep and larger areas. The high resolution radar time section, reliable geological interpretation and EL line resistivity inversion section were obtained.

There existed suspected large mined-out area within the pile number of 0~80m of buried deep below 50m. There was a big volume of mined-out area within the pile number of -30~60m of buried deep below 50m. The high resistivity distribution region of the elevation of within the pile number of -30~140m of buried deep below 120m was inferred to be an unmineralized orite layer.

The ground penetrating radar had the advantages of non-destructive and fast, which was suitable for the work under the condition of bad condition. EH4 magnetotelluric sounding method was applicable to the area with deep and wide area. It was proved that the two methods could complement each other and improved the accuracy of the evaluation of goaf.

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