Study on Evaluation Technology of Regional Grouting Treatment Effect in Limestone Aquifer of Coal Seam Floor in North China Type Coalfield Based on Two-roadway Parallel Electrical Method

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Abstract. In recent years, the regional grouting treatment technology for limestone aquifers of coal seam floor in North China type coalfield has been developed significantly. However, the detection and evaluation of water inrush risk (or treatment effect) after grouting for limestone aquifers has not yet formed a complete technical system. In view of the high cost and low amount of information of traditional grouting evaluation methods (such as water pressure test method, borehole television method, drilling core method, etc.), it is proposed to collect geoelectric data by two-roadways parallel electricity method, to process geoelectric data by the whole space three-dimensional resistivity inversion technology and to draw a three-dimensional resistivity distribution diagram. Combined with the geological structure, hydrogeological characteristics and grouting information of the detection area, the effect of grouting treatment in limestone aquifer of coal seam floor can be evaluated. This technology was applied to the detection and evaluation of the grouting treatment effectiveness to the L8 limestone aquifer of the 2-1 coal seam floor of the 11291 working face in Zhaogu No.1 Coal Mine, which effectively guided the safe production of the working face and achieved good practical effects.

1. Introduction
The distribution range of North China type coalfield starts from Yinshan Mountain in the north, to Qinling Mountain and Dabie Mountain in the south, to Helan Mountain in the west, and to the seaside (including the Korean Peninsula) in the east[1]. It includes all five provinces and cities of Hebei, Shanxi, Henan, Beijing and Tianjin, the southern part of the three provinces and autonomous regions of Jilin, Liaoning and Inner Mongolia, the central and western parts of Shandong Province, the northwest of Jiangsu Province, the north of Anhui and Shaanxi provinces, and the eastern part of Gansu Province and Ningxia Hui Autonomous Region[2].

The Carboniferous-Permian coal seams are mainly mined in the North China type coalfield. The coal-bearing strata are mainly the Taiyuan Formation of Upper Carboniferous and the Shanxi Formation of Lower Permian. The Taiyuan Formation generally contains 2 to 14 layers of thin limestone, and huge thick Ordovician limestone aquifer lies under the coal-bearing strata[3-8]. The coal-bearing strata are divided into upper coal group and lower coal group. The lower coal group is generally threatened by water damage from the limestone aquifer of coal seam floor during the mining process, and water damage accidents occur from time to time[8-11]. Grouting reinforcement has always been the main engineering technique for mining coal seam under safe waterpressure of aquifer.
In the 1950s, the main coal producing areas of Carboniferous-Permian coal seams in China began to study grouting technology for fault structures. Feicheng Mining Area and Jiaozuo Mining Area used underground roadway for drilling grouting holes and to realize grouting reinforcement of fault structures and comprehensive (or partial) transformation of working face floor[12]. Since 2008, the technical staff of Jizhong Energy Group have actively carried out research on water prevention and control theory and complete set of technologies for mining the lower coal group seams in North China type coalfield, and for the first time put forward the concept of “regional advanced treatment” for Ordovician water damage and the guiding principle “advanced initiative, regional treatment, comprehensive transformation, mining under pressure” for water prevention and control. They established the rock mechanics and fluid mechanics models of water inrush from coal seam floor, and proposed the water inrush mechanism of “divided period and section burst” on coal seam floor aquifer for the first time. They also conducted research on the grouting principle of horizontal hole in fissured aquifer, and theoretically put forward the "three-period" grout diffusion mechanism for horizontal hole in fissured aquifer, which provides a guiding theory for regional grouting treatment in fissured aquifer, grout control in complex geological structure conditions and the reasonable arrangement of treatment holes[13]. In July 2012, before tunnelling roadways and mining the coal seam of the 15445N working face in Jiulong Coal Mine, the floor aquifer and Ordovician limestone aquifer are explored and grouted by ground horizontal directional drilling technology for the first time. On January 31, 2015, the working face safely ended. In 2013, 2 drilling sites were constructed in the return air tunnel of the 11151 working face in Zhaogu No.1 Coal Mine, Jiaozuo Coal Group, and directional drilling technology and equipment were used to carry out the advanced grouting reinforcement test of the limestone aquifer of coal seam floor. A total of 6 directional drilling holes were constructed, and the length of the longest horizontal holes was 135 m, which opened up a precedent for controlling the limestone aquifer of the coal seam floor by directional drilling grouting technology in underground roadway[14]. Then, the directional drilling grouting technology was widely promoted and applied in regional water disaster control of floor aquifers of lower coal group in Hanxing Mining Area[15-18], Jiaozuo Mining Area[19-22], Huainan and Huai Bei Mining Area[10,23-26], Luxi Mining Area[27] of North China type coalfield, and good application effects have been achieved.

Scientific evaluation of the quality of grouting and plugging water project is an important guarantee for preventing water hazards and ensuring safe coal mining. At present, regional treatment projects need to be guided by corresponding theories and methods, especially the evaluation of treatment effects, which is a key step in preventing water hazards. With the application and development of directional horizontal drilling grouting technology in the treatment for water damages in the limestone aquifer of coal seam floor in North China type coalfield, China’s mine hydrogeology and engineering geologists are also constantly exploring the evaluation methods on grouting treatment effectiveness for limestone aquifer of coal seam floor. These methods currently include water pressure test method, borehole television method, inspection hole running coring method, water inflow comparison method, grout filling rate inverse algorithm, water quality comparison method, water temperature inverse algorithm, water level speculation method, grout distribution characteristic method and the safety factor method, which have certain guiding significance to the safety mining of the regional treatment working face[28]. However, due to the wide distribution of North China type coalfield in China, there are great differences in the climate, stratigraphic combination, the degree of structural development, the deposition environment and hydrogeological characteristics of thin limestone in lower coal group floor of Taiyuan Group and Ordovician limestone, at present, distance between adjacent branch holes of horizontal directional drilling grouting in limestone aquifer of lower coal group floor in North China type coalfield is generally 10–60 m[20,23-27]. The above-mentioned grouting effect evaluation methods only obtain the relevant information of the local grouting area, and the credibility of the evaluation effect needs to be further improved. Therefore, geophysicists tried to use geophysical methods to evaluate the regional treatment effect of limestone aquifers of lower group coal seam floor in North China type coalfield. In 2014, the underground directional drilling grouting technology was used to reinforce the structural weak zone and limestone water-rich zone of coal seam floor of 15248...
working face in Jiulong Coal Mine, Jizhong Energy Fengfeng Group. Anhui Huizhou Geological Safety Research Institute Co., Ltd. was entrusted to carry out comprehensive detection of the working face floor before and after grouting by using geophysical prospecting methods such as underground network parallel electrical method, radio wave perspective method and transient electromagnetic method, in order to ensure safe mining the coal seam of the working face[29]. Wu Jiwen, Zhou Shengquan and others[30,31](2014-2015) adopted resistivity CT method and seismic wave detection method to detect and evaluate the effects of the floor grouting reinforcement and aquifer reformation of the II615 working face in Hengyuan Coal Mine in northern Anhui Province, which achieved good practical results. In order to realize the accurate detection and evaluation of the grouting treatment effect in the limestone aquifer of lower group coal seam floor in North China type coalfield, it is necessary to increase the research on geophysical exploration equipment and data processing technology, on the basis of combining analyzing the geological and hydrogeological characteristics of the grouting area, to ensure safe production in coal mines.

In this paper, the two-roadway parallel electrical method was used to detect the treatment effect of the L8 limestone aquifer in the 2-1 coal seam floor of the 11291 working face in Zhaogu No.1 Coal Mine. The paper also used ground directional horizontal drilling and grouting technology and the underground fan-shaped straight-hole grouting technology(data acquisition); Whole space 3D resistivity inversion technology was used to process electrical data; Combined with the working face geological structures, hydrogeological characteristics and grouting information, the water richness of the working face floor after grouting was analyzed, and the grouting effect was evaluated. It provided strong technical support for safe mining in the working face.

2. Overview of Zhaogu No.1 Coal Mine and 11291 working face

2.1. Overview of Zhaogu No.1 Coal Mine
Zhaogu No.1 Coal Mine is located in the eastern part of Jiaozuo Coalfield and the southern foot of Taihang Mountain. It is under the jurisdiction of Huixian City, Henan Province. Its geographic coordinates are east longitude 113°33′00″~113°44′19″, and northern latitude 35°23′09″~35°28′00″.

The mine field center is 39 km away from Xinxiang City, and is connected to Xinxiang City, Jiaozuo City, Huixian City, and Huojia County via asphalt roads. It is also connected with roads in Shanxi Province via Bobi Town of Huixian City, and is 23 km away from the Huojia Station of Xinxiang-Jiaozuo Railway. The terrain of the whole area is flat, and the transportation is convenient.

The coal measure strata in Zhaogu No.1 Coal Mine are the Taiyuan Formation of Carboniferous, Shanxi Formation and Xiashihezi Formation of Permian, the mine field is typical North China type coalfield. The loose strata of Quaternary and Neogene lie above the coal measure strata, and are composed of brown-red, purple-grey and variegated clay, sandy clay, gravel and sand formed by slope, alluvial and proluvial deposits. The thickness is 366.68(hole7202)~808.10(hole 6810) m, with an average of 480.02 m, and the thickness gradually increases from north to south and from west to east. The 2-1 coal seam is primary mineable coal seam in the mine field, which has a thickness of 1.21~7.10 m (the average is 5.29 m), an inclination angle of 2~6°, a depth of 410~860 m, a vertical distance from L8 limestone of 24.08~39.89 m (the average is 31.94 m), and the strata are stable.

2.2. Overview of 11291 working face

2.2.1. Geological and hydrogeological conditions
The 11291 working face is located in the East No.3 Mining Area of Zhaogu No.1 Coal Mine, mines the 2-1 coal seam. Its upper roadway has a length of 1033 m, and the floor elevation is -336.235~372.399 m; the down roadway has a length of 835 m, and the floor elevation is -331.102~-365.727m; the mining length and width of the working face is 770 m and 200 m respectively (Figure 1).

The thickness of coal seam 2-1 is 5.3~6.5 m, and the average is 5.7 m; the false roof is carbon mudstone, with thickness of 0.1~0.7 m (average thickness is 0.4 m); the immediate roof is mudstone,
with thickness of 0.5~2.9 m (average thickness is 1.7 m); the main roof is medium sandstone with a thickness of 11.7~12.4 m (average thickness is 12.1 m); the floor is mudstone with a thickness of 0.8~2.1 m (average thickness is 1.5 m). The L8 limestone with a thickness of 8.2~8.5 m (average thickness is 8.4 m) is located about 26 m away from the floor of the 2-1 coal seam, which is rich in water. The combination of 2-1 coal seam, roof and floor of 11291 working face is shown in Figure 2.

Figure 1. The plan of 11291 working face layout and ground directional grouting holes’ trajectories

Figure 2. The comprehensive geologic column of 11291 working face

On the whole, the 11291 working face presents a monoclinal structure, and the fractured structure is developed in the working face. According to the display of 3D seismic data and the exposure of the
working face roadways, there are 22 faults in the working face, and 9 faults with the perpendicular throw of more than 2.0 m (including 2.0 m) (Figure 1).

2.2.2. **Grouting information of L₈ limestone aquifer in coal seam floor**

(1) Ground directional horizontal drilling and grouting

From June 2016 to December 2017, the ground directional drilling and grouting technology was used to drill 2 main holes (G1 and G2) on the ground. The deflecting was built at the depth of 250 m and 260 m respectively. A total of 8 horizontal branch holes were drilled in the L₈ limestone aquifer in the floor of 11291 working face (Figure 1), and the horizontal distance between adjacent horizontal branch holes of the same main hole was 48 m, in order to transform the L₈ limestone aquifer, to block the hydraulic connection channel between L₈ limestone and its lower aquifers, and to ensure the safe mining of the 11291 working face. Clay and cement were used for the grout material, and the grouting pressure was 13 MPa. The accumulated cement was 84753.56 t and the clay was 104405.00 m³. The relevant parameters of each main hole and injection branch holes are shown in Table 1.

Table 1. Grouting parameters of ground directional main holes and branch holes of L₈ limestone in the floor of 11291 working face

| Serial number | Main holes | Branch holes | Injecting material |
|---------------|------------|--------------|--------------------|
|               | Straight hole section/m | Deflecting section/m | Cement/t | Clay/m³ |
| G1 250 320    | G1-2 754.00 | G1-3 726.34 | G1-4 630.00 | G1-5 859.00 |
| G2 260 294    | G2-2 798.99 | G2-3 656.00 | G2-4 878.00 | G2-5 857.00 |
| Sum           | 6159.33    |              | 84753.56 | 104405.00 |

(2) Fan-shaped holes grouting in the underground drilling site of 11291 working face

Since the application of ground long-distance directional drilling grouting technology in the grouting reformation of coal seam floor aquifer is still in the early stage, there are relatively few studies on the diffusion mechanism of grout, and a complete and mature theory has not yet been formed. Therefore, in order to ensure the safe-mining of the 11291 working face, on the basis of directional drilling and grouting on the ground, a drill site is arranged every 100 m on the inside and outside of the upper and down roadways, and the inside drill sites and outside drill sites are staggered arrangement (Figure 1). A certain number of grouting boreholes and inspection boreholes with different directions, different inclination angles and different lengths (Figure 3) were drilled in each drill site. Grouting transformation was carried out for limestone aquifer (mainly L₈ limestone) in coal seam floor, clay- cement grout was generally used for grouting, and single-liquid cement grout was used for areas with complex geological structures.
3. Parallel electrical method and two-roadway parallel electrical method

3.1. Parallel electrical method

In 2004, Wang Hua proposed the idea that a survey line with equal electrode distance is arranged in the inspection area, to use single electrode power supply and dual electrodes power supply respectively, and the remaining electrodes measure the electric potential at the same time, through processing data indoor to realize the high-density resistivity method prospecting, including pole-pole, Wenner pole-dipole A, Wenner pole-dipole B, Wenner Alpha, Wenner Beta, Wenner Gamma, etc[33], which was regarded as the origin of parallel electric method. After nearly two decades of development, the parallel electrical method has made great progress in equipment development and data processing methods[34-38].

The parallel electrical method data gathering system is composed of a PC, a measuring host, an electrode array and a cable system. At present, most of the network electrical instruments developed are centralized 64-channel electrodes. According to the different electrode observation devices, the data gathering method of parallel electrical method can be divided into two types: \( AM \) method and \( ABM \) method[39].

(1) AM method

The electric potential field measured by the \( AM \) method(single electrode power supply method) observation system is a single-point power field(Figure 4(a)). The device is similar to the conventional pole-pole method. The arrangement uses 2 infinity poles, one is used as the electrode \( B \) supplying power, and the other one is used as a common electrode \( N \)(providing reference of standard potential). When any electrode(electrode \( A \)) of the survey line is powered, the other electrodes(electrode \( M \)) collect potential data at the same time. For data collected by \( AM \) method, high-density electrical inversion and high-resolution resistivity inversion can be carried out for pole-pole, Wenner pole-dipole A, Wenner pole-dipole B devices.

(2) ABM method
The data collected by the ABM method (dual electrodes power supply) reflects the electric field of the power supply at double opposite points, which supplies power to a pair of current electrodes A(+) and B(-). An infinity line is used as a common N pole (providing reference of standard potential), all of the other electrodes of the survey line collect the potential value (electrode M), and there is no idle electrode. Figure 4(b) shows the measurement of potential of the survey lines with 64 electrodes. For the potential and current values collected by the ABM method, high-density electrical inversion of Wenner Alpha, Wenner Beta, Wenner Gamma can be performed.

![Figure 4. The potential variation collected by parallel electrical method](image)

Parallel electrical method has been widely used in dynamic detection of roadway surrounding rock damage, geological abnormal body and water-rich abnormal area identification, groundwater seepage monitoring and water inrush warning, advanced detection of roadway excavation, grouting detection and effect evaluation, comprehensive geophysical prospecting of mines, etc[40].

3.2. Two-roadway parallel electrical method

3.2.1. Site layout and data collection

Coal seams are usually relatively high-resistivity formations, mudstone and sandstone are low-resistivity formations. Coal seams have a strong repulsive effect on the current field of the roof or floor. The electrode layout of the coal seam floor or roof usually mainly reflects the corresponding distribution of electrical properties of floor or roof of the coal seam, which can be used to detect the range of relatively water-rich areas[39].

According to scholars' theoretical research and many site experiments, for the inspection of internal structural changes in gently inclined coal seams, electrodes are usually arranged at the waist line of the roadway, so the detected electric field changes are mainly affected by the geological changes in the side wall of coal seams. Because the network parallel electric method belongs to the direct current method, the maximum effective inspection range is $AB/2$. Therefore, the maximum distance $AB$ used should be greater than the width of the working face to ensure that the current field can cover the entire width of the working face. The use of the network parallel electrical method is a good way to suppress the influence of many negative factors from metal objects, stagnant water, and stray current in the underground roadway. The inspection of thin coal areas in the coal seam has achieved significant results[41,42].

The data collected by the network parallel electric instrument is the potential value of the whole electric field, which maintains the synchronization of the potential measurement and avoids the interference problem of the potential measurement data at different times. Electrical survey lines are arranged on the floor of roadway 1 and roadway 2, using the synchronous parallel excitation current and potential collection between the two roadways (Figure 5), to form a large amount of perspective data on whole space electric field (Figure 6) between the two roadways, and to form a whole space electric collection system underground. The core of the collection system is the network parallel electrical instrument and the roadways distributed in different spaces. The 3D network parallel
The electrical method observation system can conduct rapid electrical inspection on the whole underground space. When the inspection range is large, each roadway can be arranged with multiple lines (or stations) to collect data.

![Figure 5. The schematic diagram of electrode arrangement and ray distribution the 3D space inspection by two-roadway parallel electrical method in a working face](image)

![Figure 6. The schematic diagram of stable current field in the whole underground space](image)

### 3.2.2. Data processing and resistivity imaging

The data collected by the network parallel electric instrument is the potential value of whole space electric field, which maintains the synchronization of the potential measurement and avoids the interference problem of the potential measurement data at different times. Use the network parallel electrical instrument to collect the potential changes of the survey lines in each roadway. When the inspection range is large, each roadway can be arranged with multiple stations to collect data. During data inversion, the coordinates of all electrodes in survey stations (or lines) are uniformly edited, the two-roadway electrical method collects the potential and current data of each station for splicing, and the imaging inversion of a certain depth 2D resistivity between the two roadways is jointly performed. Through the network parallel electrical processing system, the floor plan area between the two roadways is divided into 2D grids. Usually the grid division’s width is equal to the electrode spacing or 1/2 electrode spacing, and then the Jacobi matrix is solved to obtain the resistivity value of each grid. Thus, the 2D resistivity distribution between the two roadways of the working face is obtained. 2D resistivity slices of different depths are superimposed to form a 3D resistivity distribution map.

The general formula of the inverse problem of resistivity can be expressed as:

$$\Delta d = G\Delta m$$  \hspace{1cm} (1)

Where: $G$ is the Jacobi matrix; $\Delta d$ is the residual vector of the observation data $d$ and the forward theoretical value $d_0$; $\Delta m$ is the modified vector of the initial model $m$. For 3D problems, the model is
divided into 3D grids. The required parameters for the inversion are the conductivity values in each grid cell, and the observation data for the 3D inversion is the measured pole-opole potential value or pole-dipole potential value difference. Because of their wide range of variation, logarithms are generally used to calibrate the inversion data and model parameters, which helps to improve the stability of the inversion. And because of too many inversion parameters, traditional least squares inversion often leads to produce overly complex models, which are the so-called redundant structures. These redundant structural information are not required by the data itself or are indistinguishable, and bring difficulties to interpretation. Sasaki added a smooth constraint to the least squares’ criterion, and obtained a smooth model through inversion, which improves the stability of solution. The algorithm for solving the model modification $\Delta m$ is:

$$ (G^T G + \lambda C^T C) \Delta m = G^T \Delta d $$

Where $G^T$ is transposed matrix of $G$; $C$ is the smoothing matrix; $C^T$ is transposed matrix of $C$. By solving the Jacobi matrix $G$ and the calculation of the large-scale matrix inverse, the electrical data of each 3D grid is obtained. This data is particularly suitable for the use of whole space 3D resistivity inversion technology. By arranging electrical survey lines in the upper roadway and down roadway of the working face, due to the large plan area, it is especially suitable for the resistivity imaging between two roadways to obtain the electrical distribution in the working faces. The parallel electrical method is used to observe the potential changes at different positions and different elevations, and through the inversion of the 3D electrical method, the resistivity distributions in the working face and at different depths of its floor are obtained. Combined with the exposed the geological data of roadways, the geological columns of the boreholes near the working face, and the existing geophysical inspecting data of the working face, comprehensive analysis is carried out to determine the nature and distribution range of the coal seam and the floor’s geological abnormal area[43].

4. Detection and evaluation of the grouting effect of the limestone aquifer in coal seam floor of 11291 working face by two-roadway parallel electrical method

4.1. Survey line and electrode arrangement

On-site data collection of the grouting effect on the L8 limestone of coal seam floor in 11291 working face by parallel electrical method was carried out on May 11 and May 12, 2018. The electrode and electric survey lines were arranged directly on the floor of the roadway on site. The layout of the stations is shown in Figure 1, and the specific parameters are shown in Table 2. There are 6 survey stations in the upper roadway and down roadway of 11291 working face, with 64 electrodes in each station. The electrode spacing is 5 m, and the overlap between two stations is 75 m.

| Survey station (line) | Electrode B(-) | Serial number | Position | Number of | Length/m | Distance from the cut-off/m |
|----------------------|---------------|---------------|----------|-----------|----------|--------------------------|
| 1                    |               | upper roadway | 64       | 315       | 0~315    | lower roadway             |
| 2                    |               | 240~555       | 400      |           |          |                          |
| 3                    |               | 480~795       | 540      |           |          |                          |
| 4                    |               | upper roadway | 160      |           |          |                          |
| 5                    |               | lower roadway | 380      |           |          |                          |
| 6                    |               | 480~795       | 620      |           |          |                          |

4.2. Data collection

Parallel electrical method detection collects current and voltage signals, and large circuits were cut off in the detection area. The data collection adopted the YBD-11 network parallel electrical prospecting
apparatus, which can supply power at one time, receive multiple channels at the same time, suppress random noise interference on site, and effectively ensures the effectiveness of data collection.

AM method was adopted on-site data collection, in order to verify the reliability of resistivity data collection, 0.5 s and 2.0 s constant-current power supply square wave were used to collect data once respectively. Data interpretation shows that the resistivity of the two collected data was basically the same, and the quality of the original data was reliable.

4.3. Processing and analysis of inspection results

Electrical detection adopted roadway electrical sounding method, and 3D whole space resistivity inversion technology was used to reflect the changes in the electrical parameters of the floor. In the coordinate system, the intersection point of the upper roadway (hereafter, UR for short) of the 11291 working face and the outer side of the UR inside No.1 drill site is the origin of coordinates $O (0, 0, 0)$, which is 785 m away from the intersection point of the inside of the upper roadway and the inside of the open-off cut. The direction along the edge line of 11291 upper roadway’s inside pointing to the open-off cut is the $x$-axis positive direction, and the vertical direction along the edge line of the upper roadway inside pointing to the down roadway (hereafter, DR for short) is the $y$-axis positive direction, the positive direction of the $z$-axis is vertically upward.

Three stations pole-dipole electrical data of AM method in upper roadway and down roadway of 11291 working face were pieced together respectively, and pole-dipole sounding inversion calculation was performed. The results were mapped and processed by the surfer software, and the resistivity imaging horizontal sections of different depth of the floor in the working face was obtained. The top horizontal slice was -15 m horizontal slice (i.e. 15 m below the coal seam floor of 11291 working face), and the deepest horizontal slice was -75 m. The delineation of the relatively low resistance area was mainly based on the 15 Ωꞏm contour of -30 m horizontal slice. There were mainly three relatively low resistance areas, with the names of I, II, and III low resistance abnormal areas (Figure 7). The analysis of each low resistance zone was as follows:

1) Low resistance zone I: Near the upper roadway of the 11291 working face, there was a low resistance abnormal zone I(apparent resistivity $\rho_s < 15 \, \Omega \cdot m$), it was located $x = 649 \sim 709 \, m$ and $y = 20 \sim 71 \, m$, the low resistance abnormal zone extended below -45m. The main reason was that during the electrical survey period, the inside No.8 drill site and the inside No.9 drill site in the upper roadway under drilling and grouting. The UD inside 8-1 hole, UD inside 8-3 hole, and UD inside 8-5 hole were finished grouting on May 4, 2018, May 4, 2018, and May 14, 2018 respectively; the UD inside 9-1 hole, UD inside 9-2 hole, UD inside 9-3 hole, UD inside 9-4 hole, UD inside 9-5 hole and UD inside 9-6 hole was finished grouting on April 26, 2018, April 17, 2018, May 13, 2018, May 13, 2018, April 26, 2018 and May 3, 2018 respectively. The above-mentioned boreholes were all in the low resistance zone I, main reason might be that the grouting holes had short grouting end time and the grout had incomplete water loss and consolidation, as a result, the resistivity of formations in this area was low. In addition, this zone was located on the hanging wall of fault D219: $H = 0.9m \angle 68^\circ$, affected by the D219 fault, part of floor rocks may be broken and be rich in water, which increased the depth of grout diffusion depth.

2) Low resistance zone II: There was a low resistivity abnormal zone II(apparent resistivity $\rho_s < 15 \, \Omega \cdot m$) near the down roadway of 11291 working face, which was located $x = 453 \sim 492 \, m$ and $y = 111 \sim 171 \, m$, was corresponding to the area between inside No.4 drill site and inside No.6 drill site in the down roadway(DR), and extended below -60 m. Main reason might be that the DR inside No.5 drill site and DR inside No.6 drill site in the zone had just been constructed, namely, the DR inside 5 inspection 3 hole, the DR inside 5-6 hole, the DR inside 5 inspection 5 hole, the DR inside 5 inspection 6 hole, the DR inside 5 inspection 7 hole was finished grouting on April 13, 2018, April 18, 2018, April 30, 2018, April 30, 2018 and May 14, 2018 respectively; the DR inside 6 inspection 4 hole, the DR inside 6 inspection 5 hole, the DR inside 6 inspection 6 hole, the DR inside 6 inspection 8 hole was finished grouting on April 15, 2018, April 15, 2018, April 22, 2018 and May 18, 2018 respectively. This zone was located between fault D200: $H = 1.35 \sim 1.90 \, m \angle 80^\circ$ and fault D207:
H=0.2~0.8m ∠80° (that is, located at a graben). Under the influence of tectonic stress, local rock mass of coal floor might be broken or rich in water, and the depth of grout diffusion would increase. The water used during the construction of each drill site would penetrate the floor rock and the fault fracture zone, the end time of drilling and grouting of the above-mentioned holes were all short, and the grout was not completely dehydrated and consolidated. As a result, the apparent resistivity of the floor in this area was low.

Figure 7. The overall spatial distribution of the anomalous resistivity zone of the floor in 11291 working face

(3) Low resistance zone III: There was a low-resistance abnormal zone III (apparent resistivity $\rho_s<15 \ \Omega\cdot m$) near the down roadway of the 11291 working face, which was located $x=303~328 \ m$, $y=135~177 \ m$, corresponding to the area between inside No.3 drill site and inside No.4 drill site in the down roadway (DR) of the working face, and extended below -30m. The main reason was that during the electrical inspection period, the grouting boreholes of the floor of the inside No.4 drill site in the down roadway were under drilling and grouting, the DR inside 4-1 hole, the DR inside 4-2 hole, the DR inside 4-3 hole, the DR inside 4-4 hole, the DR inside 4-5 hole, the DR inside 4-6 hole and the DR inside 4-6 hole was finished grouting on April 14, 2018, April 24, 2018, April 14, 2018, April 24, 2018, April 19, 2018 and May 4, 2018 respectively. In addition, this zone was located at the hanging wall of the fault D199: H=2.0 ∠41°, and the local stratum was relatively broken. The water used in
the construction of the underground drill site would penetrate the floor rock and the fault fracture zone. The end time of drilling and grouting of the above-mentioned holes were all short, and the grout was not completely dehydrated and consolidated. As a result, the apparent resistivity of the floor in this area was low.

(4) Other low-resistance areas: Figure 6 showed that in the resistivity slice map of -15 m floor, there were 8 low-resistance zones (apparent resistivity $\rho_s < 15 \, \Omega \cdot \text{m}$) scattered around upper roadway and down roadway. None of the zones extend to the depth of the -30 m floor, and the analysis believed that these were mainly caused by water drenching from the sandstone in the roof of the roadways (the roadways near the above 8 zones had different degrees of water drenching).

4.4. Evaluation of grouting effect

Before the electric detection of 11291 working face, Zhaogu No. 1 Mine used underground drilling to carry out supplementary grouting construction on the coal seam floor of the working face. The final depth of each borehole passed through L8 limestone, during drilling construction, the water inflow of some holes exceeded 30 m$^3$/h. Among them, the water inflow of the DR inside 5 inspection 5 borehole was the biggest one, it was 80 m$^3$/h in the period of drilling. It showed that after the ground directional drilling was used for grouting in the L8 limestone of the coal seam floor in 11291 working face, there were still partial water-rich areas.

According to the electrical detection results in figure 6, it could be seen that after the grouting of the coal seam floor in 11291 working face through the ground directional-hole grouting and the underground fan-shaped-hole grouting, the electrical properties of the floor changed significantly, except for some zones with low apparent resistivity. The apparent resistivity of most zones was relatively high, indicating that the grouting effect of the working face was relatively significant, in other words, the L8 limestone aquifer and the water-bearing fault fracture zones were transformed into a water-resistant layer (or a weak aquifer) and complete rock masses. The three low-resistance abnormal zones (I, II and III) were mainly caused by the short completion time of grouting in some underground boreholes (1~20 d) and the water in the grout had not yet precipitated. The risk of water inrush in the 11291 working face would be small in the near future mining process, but in order to ensure safety, necessary water prevention and control measures should be taken before mining the coal seam in the three low-resistance abnormal zones.

5. Two-roadway parallel electrical inspection and evaluation results verification

The mining of 11291 working face of Zhaogu No.1 Mine was started on July 1, 2018 and ended on June 30, 2019. The strike mining length of the working face was 757.2 m. There was no water inrush accident during the mining process, and a total of 1.28 million tons was mined, with an average of about 3,500 tons every day. The two-roadway parallel electrical inspection had played an important role in guiding the safe and efficient production of the working face.

6. Conclusions

(1) The paper introduced the principle, data collection and processing technology of parallel electrical method and two-roadway parallel electrical method, and applied the technology to the engineering practice of effect evaluation of grouting treatment on the limestone aquifer of coal seam floor in North China type coalfield, which enriched the evaluation method of the effect of grouting on coal mine aquifer.

(2) Using two-roadway parallel electrical method and whole space 3D resistivity inversion technology, it could more clearly reflect the electrical changes and distributions after grouting treatment on limestone aquifer of the coal seam floor in North China coalfields. Combined with the detection of regional structure, hydrogeological characteristics and grouting information, comprehensive analysis and evaluation of grouting effects could provide technical support for the safe mining of limestone confined water coal seams in North China coalfields.
(3) The research on the relationship between the degree of water loss and consolidation of the grout (single-liquid cement grout, clay-cement grout, cement-sodium silicate grout, etc.) in the deep-buried stratum environment, on the electrical conductivity and effect of the grout, and on the parallel electrical data inversion should be increased, so as to realize the fine detection and accurate evaluation of the grouting treatment effect on the limestone aquifer of coal seam floor in the lower coal group of the North China type coalfield, and to better serve the safe production of coal mines.

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