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Key Strata Identification of Overburden Based on Magnetotelluric Detection: A Case Study

Yunguang Wang [1,2], Wenbing Guo [1,3], Erhu Bai [1,3,*] and Yuxi Wang [4]

1 School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, China; mwang110@126.com (Y.W.); guowb@hpu.edu.cn (W.G.)
2 Huizhou Urban Transportation Planning Institute, Guangdong 516000, China
3 Synergism Innovative Centre of Coal Safety Production in Henan Province, Jiaozuo 454003, China
4 Henan Jinghui Technology Co., Ltd., Zhengzhou 450000, China; nengyuan316@126.com
* Correspondence: baieh@hpu.edu.cn; Tel.: +86-1513-800-2536

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Abstract: The severe overburden failure induced by high-intensity mining is the essence of eco-environmental problems in Northwest China, and the degree of overburden failure is closely related to the location and failure of key strata (KS), which controls part of the strata in the overburden. In order to solve the problems of traditional KS based on mechanical parameters and numerical simulation methods that are time consuming, complex, expensive, and work intensive, it is necessary to find a simple and fast KS identification method. Based on the KS theory, which has been successfully applied in the field practice for nearly 30 years, and its current identification method by calculation or software, the magnetotelluric (MT) detection method was selected. According to the principle of MT detection method, the main influencing factors were analyzed. By summing up the relationship between the geological characteristics of the KS and its apparent resistivity (AR), the AR trends of ten kinds of lithology are given, and the identification mechanism of the MT detection method is revealed. Through the field measurement in Daliuta coalmine and the accuracy verification by the theory calculation, the KS obtained by the two methods are consistent. The results show that the MT detection method can be used to quickly identify the KS, and it is simple, convenient, and fast. It provides a reference for optimizing mining technology, mine pressure control, and mine precision.

Keywords: key strata; magnetotelluric (MT) detection; apparent resistivity (AR); overburden failure

1. Introduction

China is a large coal producer and energy consumer, which is mainly because coal is the primary energy source and provides the basis of the energy infrastructure necessary for long-term, rapid economic growth [1]. With the continuous development of mining methods, technical equipment, and the Internet, the high-intensity mining of thick coal seams has become an important development direction of China's coal mining technology, especially in the fragile eco-environment area of Northwest China [2]. However, the exploitation of coal resources can lead to a series of serious environmental problems, the essence of which is that the overburden failure is relatively severe [3,4]. Moreover, the degree of overburden failure is closely related to the location and failure of key strata (KS) [5–10]. As is well-known, the overburden is composed of different strata with variable characteristics; thus, the mining effects on each stratum is different. For the hard and thick strata, they may have a stronger bearing capacity, supporting those weak and thin strata that only act as loads. Based on these differences, the KS theory was proposed [11]. According to the KS theory, the hard and thick stratum is named KS; as a result, overburden has at least one KS. If there are more than two KS, as shown in Figure 1 [12], the top KS is named the primary KS (PKS), as it bears the entire load from its roof to ground surface. Correspondingly, the other KS is named the sub-key strata (SKS), that controls partial overburden strata [13].

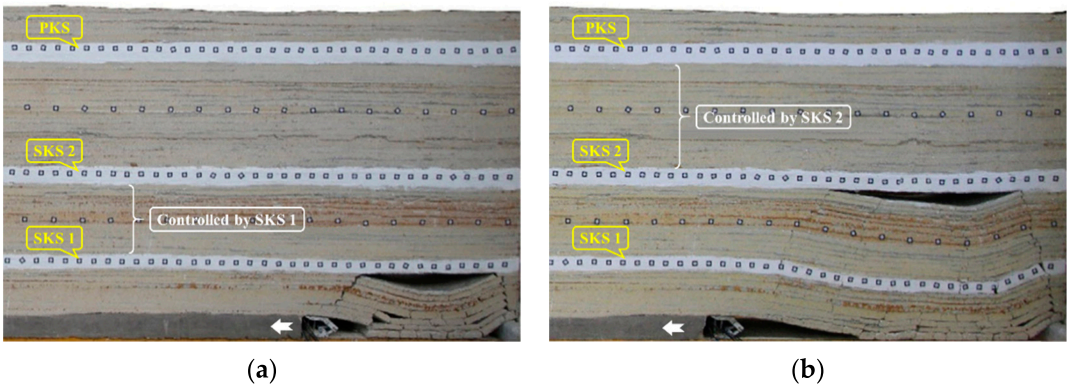


Figure 1. Control effect of key strata (KS) in overlying strata movement; (**a**) the control effect of sub-key strata 1 (SKS1) from the SKS1 roof to the SKS2 floor; (**b**) the control effect of SKS2 from the SKS2 roof to the primary KS (PKS) floor.

At present, the identification method of KS mainly relies on the lithology calculation, ground drilling, and laboratory simulation. Wen et al. [14] found that the key stratum has a significant impact on the behavior of the strata in a stope by theoretical calculation, and divided it into a "single key stratum" structure and a "double key strata" structure. Ju et al. [15] adopted in-situ investigation of surface boreholes and found a strong correlation between dislocation inside the boreholes and the location of the key strata, from which the fracture and movement of the key strata with the advancing process of the working face was inverted. Kuang et al. [16] carried out an in-situ investigation to determine the law of fracture and movement of a key stratum. Li et al. [17] defined the movement type of SKS by theoretical analysis and numerical simulation, and verified the correctness of the support working resistance formula under different types by field measurement. Xie and Xu [18] used numerical simulation methods to study the key strata with different thicknesses and heights, and got the relationship between the key strata and the abutment pressure. Meanwhile, Xu and Qian [19] developed the distinguishing software of key strata with the C# language.

Based on the existing references, the identification of KS needs to be calculated according to the rock's mechanical parameters. However, for the mining areas with unknown mechanical parameters, it is important to find a proper way to accurately identify the KS in order to avoid the time-consuming, complex, and labor-intensive of the laboratory simulation method, so as to ensure the safety production and mine pressure control. Combined with the development of geophysical exploration, it has become a hot topic in detecting overburden structure and failure [20–23]. Among the methods, magnetotelluric (MT) detection is a simple and convenient one, which has been applied to the identification and detection of water-rich coal seams, thin interbeds, overburden failure, geothermal resources, karst, collapse areas, fault structures, and overburden fractures in the goaf area. Some engineering application examples of MT detection method in coalmines are shown in Table 1.

Table 1. Examples with magnetotelluric (MT) detection technique in mines.

Year	Site	Purpose	Depth (m)
2007	Jiaozuo mining section of South-to-North Water Diversion Project, Henan	Goaf distribution	410
2008	Concealed mine area, Fujian	"Three-under" coal mining	1500
2009	Bauxite mining area of Mianchi county, Henan	Identifying thin interbed	600
2010	Hongliu Coalmine, Ningxia	Height of water flowing fracture zone	350
2011	Panyi Coalmine, Anhui	Overburden failure characteristics	360
2012	Coalmines of Xinjiang & Shanxi	Goaf location and aquifer distribution	400
2014	Jingdong Coalmine, Shanxi	Goaf distribution	200
2015	Tectonic fault basin, Northeast Inner Mongolia	Coal mining	500
2016	Liudong Coaimine, Anhui	Structure exploration	900

As shown in Table 1, the detection depth is less than 1500 m, mostly less than 600 m though. Moreover, the detection results are basically consistent with the actual situation, which provides technical support for the MT detection technique to analyze key strata of overlying strata. Therefore, it is necessary to study whether MT detection can be applied to the identification of KS.

2. MT Detection Method

2.1. Technical Principle

With the development of MT detection technique, new technical means have been provided for the detection of overburden structure and fractures. It is an important geophysical means to study the electrical structure of the earth's interior with the natural electromagnetic field as the field source [24]. Although rock resistivity is affected by many factors, under certain conditions, its resistivity is a constant value and has certain regularity. For example, the resistivity of rocks in the same area, age, and lithology is generally similar. Therefore, as long as the resistivity characteristics of various rocks are mastered, geological sections can be divided. The results of data inversion technology reveal that the geological characteristics of rock strata are visual, accurate, and efficient. Different lithology has obvious differences in material composition, cements, and consolidation. According to the skin theory, different strata contain their corresponding frequencies and amplitudes. By detecting the electromagnetic wave signal, lithology and fluid information of different depth strata, the underground lithology interface, and the structure can be analyzed. Therefore, its basic principle is to analyze the surface material depth and electrical structures of electromagnetic waves with different frequencies when they pass through the strata, and to obtain the electromagnetic response array of the earth with these frequencies from high to low, as shown in Figure 2. This is because different strata have different compositional, cement, and consolidation properties [25], which can be used to analyze the overburden nature, activity, interface, coal seam, aquifer, geothermal activity, and geological structure.

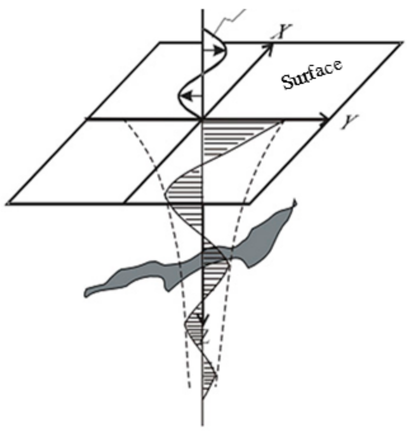


Figure 2. A sketch of the MT detection principle.

Based on its technical principle, it has the advantages of higher resolution, great depth detection, low cost, and easy construction. In theory, wave impedance is a ratio that electric field E and horizontal component of magnetic field H in the uniform and horizontal layered strata (Equations (1)–(3)).

$$Z = \left|\frac{E}{H}\right| e^{i(\varphi_E - \varphi_H)} \tag{1}$$

$$\rho_{xy} = \frac{1}{5f}\left|Z_{xy}\right|^2 = \frac{1}{5f}\left|\frac{E_x}{H_y}\right|^2 \tag{2}$$

$$\rho_{yx} = \frac{1}{5f}\left|Z_{yx}\right|^2 = \frac{1}{5f}\left|\frac{E_y}{H_x}\right|^2, \tag{3}$$

where: f—frequency, Hz; ρ—resistivity, Ω m; E—electric field intensity, mv/km; H—magnetic field intensity, nT; φ_E—electric filed phase; φ_H—magnetic field phase, mrad.

The skin depth (δ) is propagation depth when the amplitude attenuation of electromagnetic wave (E, H) decays to 1/e of the initial value in the strata, as shown in Formula (4).

$$\delta = 503\sqrt{\frac{\rho}{f}} \tag{4}$$

According to the above formula, skin depth varies with resistivity and frequency. It can be seen that when the resistivity is a constant, the propagation depth or detection depth of electromagnetic wave is inversely proportional to the frequency; i.e., high frequency corresponds to electrical property features in shallow strata, and vice versa. Therefore, the different frequency electromagnetic waves can be used to identify the strata depth. Moreover, the apparent resistivity (AR) and apparent phase can be calculated by observing the electric and magnetic field information in the broadband. Subsequently, the geoelectric characteristics and strata structure can be determined. Based on the characteristics of key strata, the relationship between the geological characteristics of overburden KS and its AR response are shown in Figure 3. Therefore, based on its basic principle, combined with inversion analysis and visualization technology, the KS of overburden can be identified.

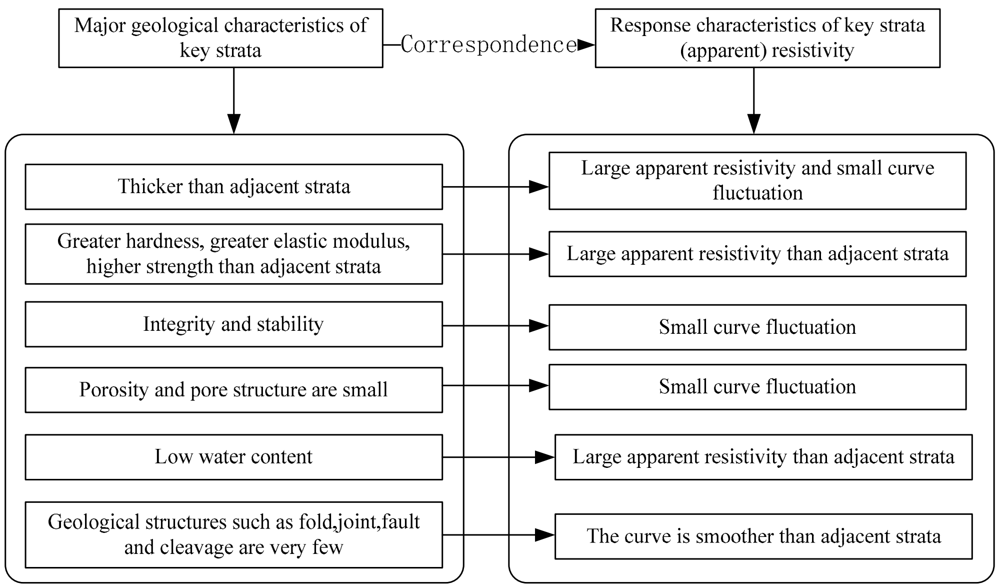


Figure 3. Relationship between KS characteristics and its apparent resistivity (AR) response.

2.2. Influencing Factors

Resistivity is a parameter used to describe the physical properties of rocks under ideal conditions. Under natural conditions, in addition to rock components, there are many factors that affect the rock's resistivity, including structure, porosity, water content, etc. [26]. Due to a stratum being a combination of many materials and structures, it is difficult to accurately calculate its resistivity. Consequently, resistivity is replaced by AR in the research and engineering. Thus, AR is not a real resistivity value, but a parameter reflecting the comprehensive characteristics of overlying strata, and a comprehensive product that reflects the conductivity and topography of strata. Formula (5) is the calculation of AR.

$$\rho_s = K\frac{\Delta U_{MN}}{I}, \tag{5}$$

where K is electrode coefficient; I is measured current, A; ΔU_{MN} is potential difference, V.

Because there are a large number of fractures, structures, water, and other fluids or other conductive media in the strata, the resistivity value of a stratum is less than its AR. The AR of overlying strata with high porosity and permeability obviously depends on the fluid and conductivity. In general, dense strata have fewer pores, fluids, and higher AR, and vice versa. Meanwhile, the main influencing factors of AR are shown in Figure 4.

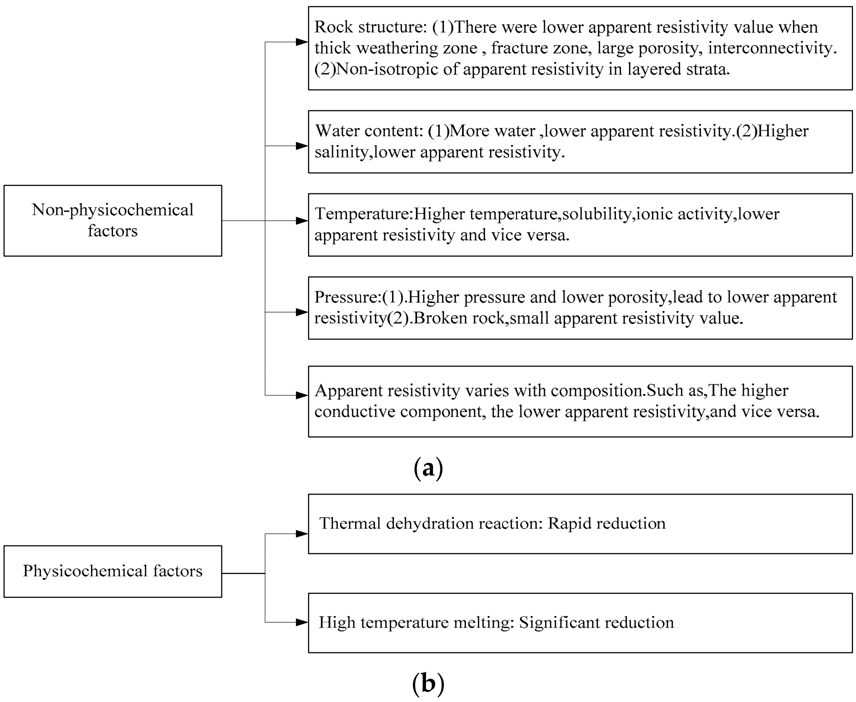


Figure 4. The main influencing factors of AR: (**a**) non-physicochemical factors; (**b**) physicochemical factors.

3. Identification Mechanism of MT Detection

3.1. The Characteristics of Overburden AR

The characteristics of overburden AR can be obtained by using the inversion technology [27]. The instrument used this time was a CAN-I MT lithology detector produced by Zhengzhou City, Henan Province, China. Through the comparison and analysis of the detected characteristic points and the borehole histogram, the relationship between the AR and the stratum lithology was obtained. For the mining area without accurate mechanical parameters, the AR characteristics of different strata can be used to determine the lithology of strata. Figure 5 shows the AR characteristic of 10 kinds of rock strata, which come from the Buertai coalmine near the study area.

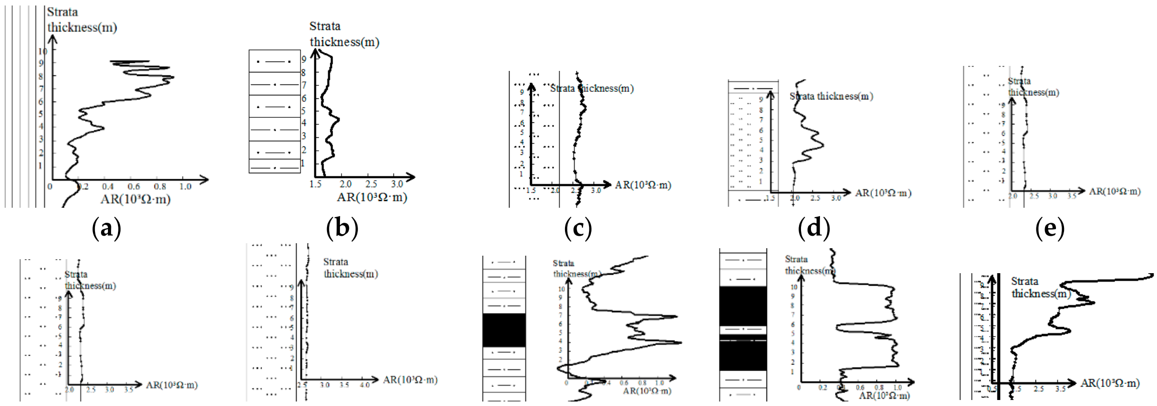


Figure 5. Characteristics of MT responses of common overlying strata: (**a**) quaternary loose layer; (**b**) sandy mudstone; (**c**) fine-sandstone; (**d**) medium sandstone; (**e**) coarse sandstone; (**f**) mudstone; (**g**) siltstone; (**h**) coal seam; (**i**) coal-rock interbed; (**j**) conglomerate.

As shown in Figure 5, it can be seen that the AR of different strata have different trends. The AR curve of a dense and single component stratum is smooth, and the curve fluctuation is small, while the unconsolidated layer has a significant fluctuation because of its porosity and many components. In addition, under the dry condition, the denser the stratum is, the larger the AR is, and vice versa.

3.2. Strata Identification Mechanism

In order to identify strata, many researchers have studied the "threshold value" of AR [28,29]. Based on the basic principle of MT detection, the lithology and thickness of strata can be determined by studying the characteristics of AR curve of different strata, so as to identify each stratum. According to the principle of relative error of AR in one-dimensional medium model, a method of identifying strata is provided, as shown in Equation (6).

$$\eta = \left| \frac{\sum_{i-1}^{n} \rho_i - n\rho}{n\rho} \right| \times 100\%, \ (i = 1, 2, 3 \cdots n). \tag{6}$$

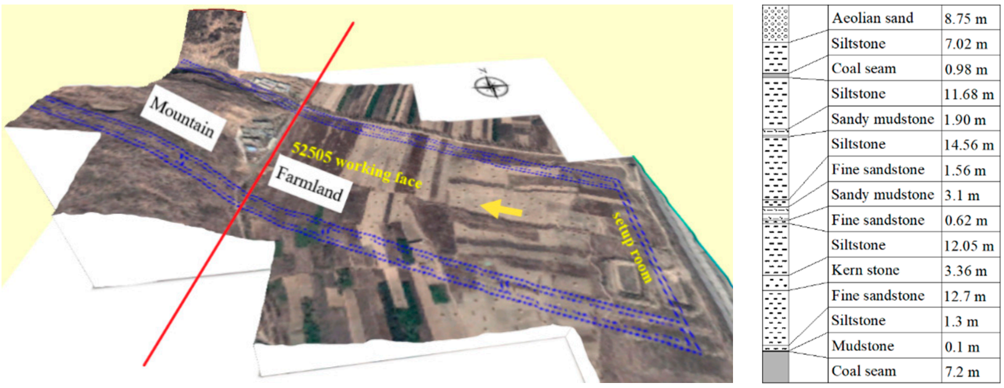
Generally, ρ is uniform half-space resistivity without thin layer; i is each frequency point's AR in the presence of a thin layer. In this paper, the relative error of 5% AR is taken as the resolution standard; that is, when the relative error of overburden AR is greater than 5%, it will be regarded as a distinguishable anomaly.

4. Engineering Application

4.1. Region Overview

The Daliuta coalmine (in Shenmu District, China) has a designated capacity of 21.7 million t/a. The mineable coal is the number 52 coal seam of the Yan'an Formation of the Triassic system with an average thickness of 7.2 m and average buried depth of 90 m; it has a stable horizon and simple structure. According to the concept of high-intensity mining [30], the 52,505 working face, located in the number 5 panel, belongs to high-intensity mine with a length of 4268 m, a width of 301 m, and a mining speed is 13.84 m/d. The working face adopts large mining height technology and the caving method to manage the roof. The surface topography above the working face and the drilling histogram of working face are shown in Figure 6.

Based on the engineering design and the high-intensity mining technique characteristics [2,31], the overburden and surface will be seriously damaged after the 52,505 working face has mined, which could easily lead to geological disaster and environmental damage. Therefore, it is suitable for MT detection.



(**a**) (**b**)

Figure 6. Surface topography above the working face and the drilling histogram of working face: (**a**) surface topography and landform of panel; (**b**) borehole columnar section.

4.2. Observation Scheme

According to the geological condition and its surface topography, it is a convenient area for MT detection from setup room to 550 m of the advancing length of working face, while the area from 550 m to 4268 m is not suitable for detection because of it is aeolian sand gully area with a drop of up to 140 m. Consequently, the relatively flat area above the setup room of working face was selected for MT detection to identify the KS. Four detection lines were set on the ground surface (as shown in Figure 7), wherein the A, B, and C lines were parallel to the width of working face, and the distance between adjacent two lines was 200 m. The D line was parallel to the length of working face and located at center. The distance between measuring points was 10 m.

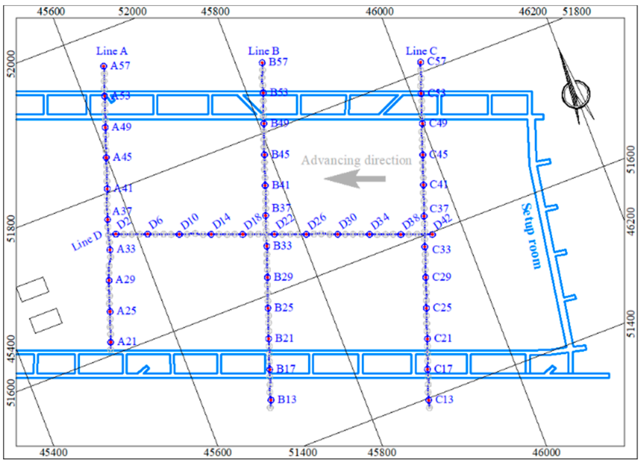


Figure 7. Plane position diagram of MT detection lines and working face.

4.3. Key Strata Analysis and Discussion

In order to study the KS characteristics of working face, two MT detections have been carried out with an interval of 60 days. The analysis of AR from characteristic points, major sections, and KS, is as follows.

4.3.1. AR of Characteristic Points

According to the characteristics of surface deformation and the KS failure, the inflection point of surface subsidence curve is located at the boundary of goaf; the maximum surface subsidence is located at the middle of working face under the condition of horizontal coal seam. Therefore, the measuring points located in these two positions can be regarded as characteristic points, which is most conducive to identifying the overburden KS; namely, A21, A35, B20, B35, D16, and D26. The AR distribution of characteristic points before and after mining are shown in Figure 8.

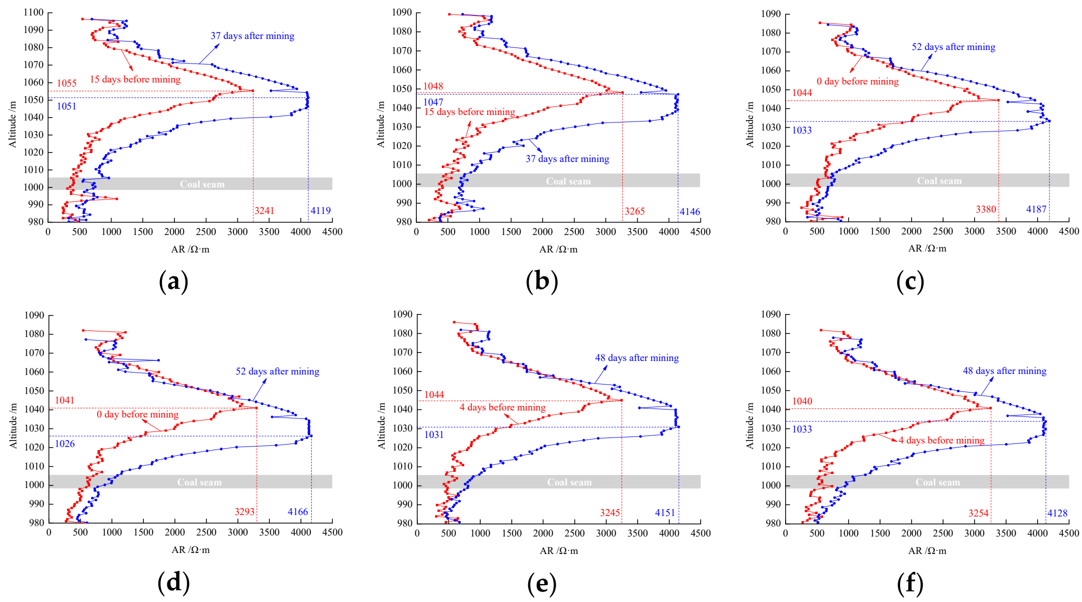


Figure 8. The AR distribution of characteristic points before and after mining: (**a**) Point A21; (**b**) Point A35; (**c**) Point B20; (**d**) Point B35; (**e**) Point D16; (**f**) Point D26.

From the above figure, the AR distribution trend of characteristic points is basically the same before mining. The maximum AR is at altitude of 1040–1050 m. But it decreases rapidly on both sides of the curve in the maximum area and loose layer. According to the influencing factors of AR and MT response characteristics, it can be seen that the geological characteristics were simple and the strata were stable. However, at an altitude of 1040–1050 m, the AR trend is different with the adjacent strata. Through the analysis of AR before and after mining, the following results can be obtained: (1) the AR values after mining are larger than before mining at the same depth; (2) the position of the maximum AR moves down before mining, and the trend is the same as overburden failure; (3) the AR curve could be divided into two parts after mining: small change zone and large change zone. The boundary of the two parts is clear. Based on the KS failure characteristics and above analysis, the KS can be preliminarily determined near the position of the maximum AR before mining.

4.3.2. AR of the Major Section

In order to obtain the characteristics of KS, the AR characteristics of line B and line D are analyzed (as shown in Figure 9).

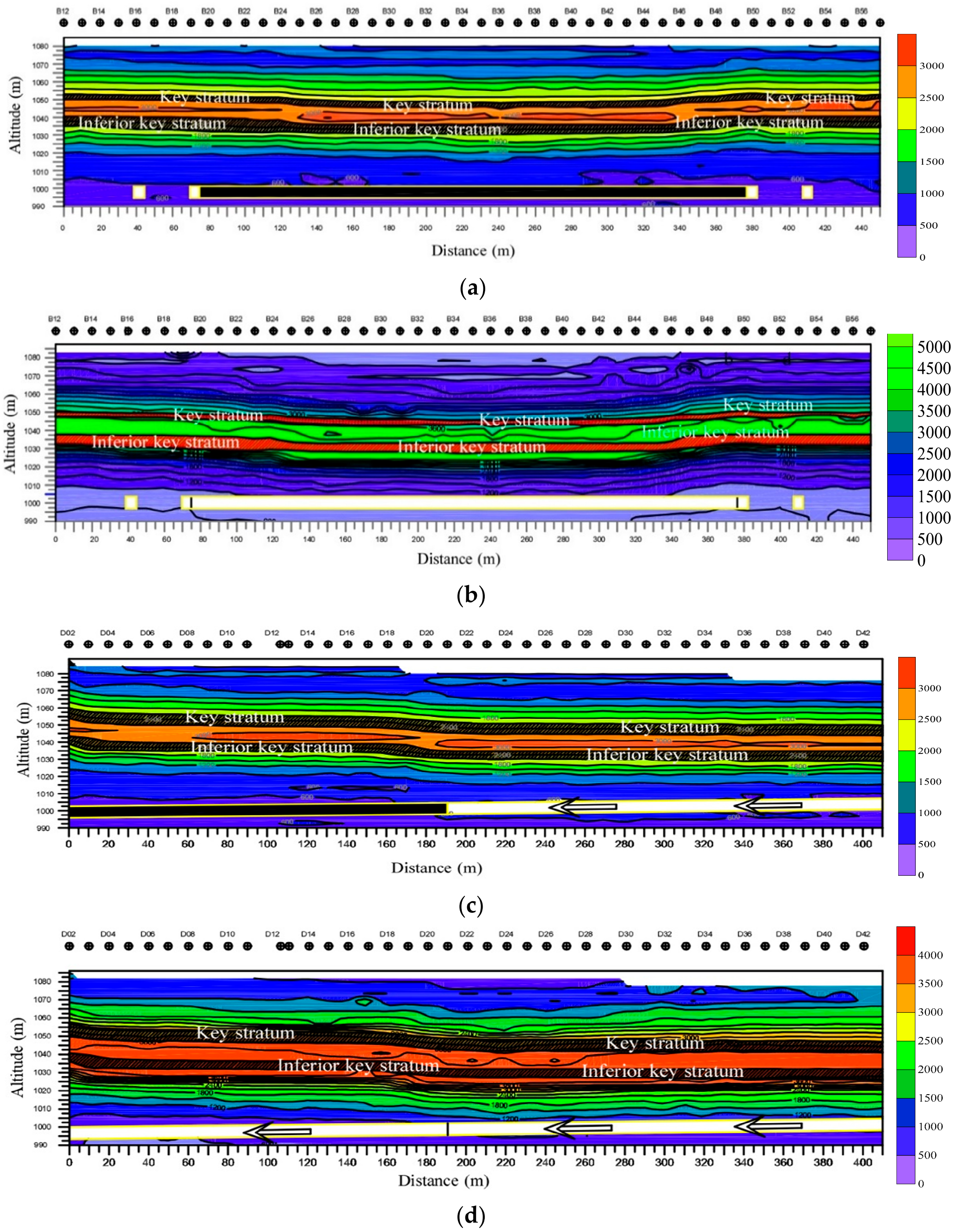


Figure 9. The AR characteristics of lines B and D: (**a**) line B before mining; (**b**) line B after mining; (**c**) line D before mining; (**d**) line D after mining.

From the Figure 9, the maximum AR of these two lines is at an altitude of 1042.5–1052.5 m before mining, and the strata are locally discontinuous. According to the basic principle of MT detection, the strata may have initial fracture or tectonic fracture in this area, but the strata located the upper and lower have a better layered structure before mining. Based on the KS characteristics and its function on the overburden failure, the area (1042.5–1052.5 m) with a large AR and initial fissure is not suitable for KS. However, the strata located the upper and lower are suitable.

4.3.3. KS Characteristics

According to the identification mechanism of MT detection in the working face, there are two KS in the overburden: one is of the average thickness 7.1 m at the altitude of 1048.3–1055.4 m (average depth is 32.11 m); the other is of the average thickness 7.6 m at the altitude of 1034.9–1042.5 m (average depth is 44.48 m). The average distance is 8.6 m between the PKS and SKS. Based on the AR characteristics, the densification of isogram near the KS after mining in Figure 9b,d is caused by the closure of primary fracture or the loss of groundwater after the strata re-compacts with the failure of KS. That is, the PKS and SKS have played an important role in the process of overburden failure, which is also consistent with the KS theory.

4.4. Reliability Verification

In order to verify the credibility of MT detection, a theoretical calculation of KS was selected for comparison. Based on the KS theory, the KS can be calculated according to the mechanical parameters, such as thickness, bulk density, elastic modulus, and tensile strength. Therefore, the parameters and results are shown in Table 2.

Table 2. Mechanical parameters of overlying strata and KS location.

Number	Lithology	Thickness h (m)	Bulk Density γ (kg/m^3)	Elastic Modulus E (GPa)	Tensile Strength σ_c (MPa)	KS Location
1	Aeolian sand	8.75	1600	/	/	
2	Siltstone	7.02	2650	40	3.83	
3	Coal	0.98	1400	/	0.80	
4	Siltstone	11.68	2650	40	3.83	
5	Sandy mudstone	1.9	2520	18	1.53	
6	Siltstone	14.56	2650	40	3.83	PKS
7	Fine sandstone	1.56	2680	37	2.70	
8	Sandy mudstone	3.1	2520	18	1.53	
9	Fine sandstone	0.62	2680	37	2.70	
10	Siltstone	12.05	2650	40	3.83	SKS
11	Kern stone	3.36	2580	27	2.10	
12	Fine sandstone	12.7	2680	37	2.70	
13	Siltstone	1.3	2650	40	3.83	SKS
14	Mudstone	0.1	2250	8	1.23	

It can be seen that the buried depths of KS are 30.33 and 47.66 m, respectively, and the spacing between them is 8.94 m. That is basically consistent with the result of MT detection, indicating that MT detection can be used to identify KS quickly and conveniently.

5. Conclusions

(1) Overburden failure will inevitably lead to the changing of electromagnetic characteristics. Due to the different degrees of failure, the overburden AR characteristics with different buried depths are different. In theory, the more severe of overburden failure after mining, the greater change of apparent resistivity.

(2) According to the field application, the strata characteristics revealed by MT detection are consistent with KS, especially in the aspect of lithology, mechanical properties, failure characteristics, and electromagnetic response characteristics, which provides a basis for the analysis of KS in MT detection.

(3) Based on the comparison between field application and analysis, MT detection can be used as a convenient and fast method to identify the overburden KS by analyzing the AR characteristics, which provides a new technical support for the mine pressure control, construction of digital model, and precise mining.

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