

Article

Surface Water Resource Protection in a Mining Process under Varying Strata Thickness—A Case Study of Buliangou Coal Mine, China

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Abstract: The mining of shallow buried and thick coal seams may cause ground settlement, loss of surface water, and even soil desertification in arid–semi-arid climate zones. The key to protecting surface water resources through the technology of separated strata grouting is to study the evolution of the separation space under the key stratum (KS) with the change of strata. Aiming at the section of underground strata characteristics of F6202 and F6208 working faces, similar simulation tests under three typical geological conditions were carried out. Based on the experimental results, a theoretical calculation model was established, and the practice of separation grouting was carried out. The results show that, under the conditions of a thick coal seam with one KS, the structure formed by breaking strata below the KS was relatively unstable, and the separation space was relatively large, which is likely to cause serious ground settlement. More seriously, with the increase of the weakly consolidated layer and coal seam thickness, the increase of the ratio of rock to soil in the weakly consolidated layer, and the decrease of the thickness of the strata below the KS (two KS condition), the separation space was further increased. Based on the above analysis, combined with the real-time feedback data of the grout amount and pressure on hydraulic support, the position of the grouting borehole was determined, and the speed of mining advance was adjusted in time, thus effectively controlling the curvature of the ground settlement, protecting the integrity of the red clay layer near the surface, and consequently protecting water resources.

Keywords: surface water resources; varying strata thickness; separated strata grouting; similar simulation tests; theoretical calculation

1. Introduction

Surface water resource protection is of great significance to prevent desertification. In fact, land desertification is a major global ecological problem that affects one-fifth of the world's population and one-third of the land [1]. In China, desertification land is distributed in 30 out of 34 provinces, making it one of the most severely desertified countries in the world. In particular, in the coal-producing area in northwest China, with an arid or semi-arid climate zone, surface water resources will be

seriously affected by underground coal mining under the conditions of shallow mining depth and huge mining height, such as river cut-off [2] and decline of groundwater level [3]. This effect will lead to the death of some surface vegetation [4], cause the swamp and wetland to dry up [5], resulting in the formation of desertified land.

The key to preventing this artificial ecological disaster is to figure out the characteristics of overlying strata movement during the mining process and to adopt reasonable management methods in different geological conditions. Esaki et al. [6] predicted the profile function of river bed settlement under the condition of deep mining depth using continuum mechanics combined with geographic information system (GIS) technology. Through similar simulation experiments, Yan et al. [7] analyzed the influence of different topsoil thicknesses and step beams caused by mining on surface cracks. Based on “voussoir beam” theory [8], Zhu et al. [9] studied the law of ground settlement under the condition of a thin coal seam using a theoretical calculation method. Using the Levenberg–Marquardt algorithm for nonlinear curve fitting of ground settlement data in the Fushun mining area, an inverse tangent function model was proposed by Nie et al. [10] to predict curves of ground settlement under conditions of a thick hard rock stratum. Some scholars believe that protecting surface water resources and preventing water inrush from the surface to the mining face are two aspects of the problem. In response to the threat of submerged aquifers to coal mines, Chen et al. [11] obtained the envelope of the caving zone and fracture zone under the condition of only one hard rock in the roof using the finite element method. Wu et al. [12] obtained the height of the water conducted zone using a numerical simulation method, and combined the aquifer water-abundance distribution charts to infer the area with water inrush risk. For management methods, the backfill mining [13] and strip mining [14] methods may be the best ways of protecting the surface water environment. However, the huge cost of the former and the low recovery ratio of the latter restrict the promotion of the two methods [15]. According to the geological conditions of thick sandstone above the coal seam, Chen et al. [16] injected cement slurry into the separated space under the key stratum (KS) to ensure the integrity of the KS and its upper rock strata, thereby reducing ground settlement.

As mentioned above, most scholars studied the law of overburden strata movement and ground settlement in the mining process using a series of methods; at the same time, a variety of techniques to protect water resources were adopted. However, they did not pay more attention to geological factors, such as the number of KS, as well as the variation of strata and coal seam thickness. In fact, the distribution of rock strata in the stratigraphic section is usually uneven. If this varietal thickness is simplified to a certain thickness, the results will have a large deviation from the real situation. In addition, systematic problems require system thinking and system techniques to solve. For these methods, similar simulations and block mechanics suitable for the analysis of broken rock strata seem to be better choices than continuum mechanics methods. For the technology, separated strata grouting with characteristics of low cost and high efficiency has more advantages; however, its implementation according to laboratory and in situ test results is a problem.

In this article, F6202 and F6208 working faces in Buliangou coal mine were selected as the study areas, where there are several rivers on the surface. The average mining height and depth was about 10 m and 200 m, respectively. At the same time, the thickness of the strata in coal seam roof changes greatly. In order to protect surface water resources, we used separated strata grouting technology to reduce the mining effect of on the key aquifuge red-clay layer. By establishing a similar model under three typical geological conditions, along with the calculation model, and combining with the monitoring results of rock pressure and grout amount, the basic parameters of grouting practice were obtained. In situ tests showed that separated strata grouting technology with reasonable parameters can prevent the loss of surface water resources under mining influence. This article provides a useful reference for surface water conservation and desertification control under the coal mining influence in arid–semi-arid regions.

2. Study Area

Compared to the late Paleozoic coalfields with simple geological structures and thin-medium-thickness coal seams exploited in other parts of the world, such as the Appalachian coalfield in the United States [17], the Yorkshire coalfield in Great Britain [18], the Ruhr coalfield in Germany [19], the Donetz coalfield in Ukraine [20], and Yongxia, Huainan, or other coalfields in East China [21], there is great impact on the surface water resources during the mining process in the Zhungeer coalfield due to it being adjacent to the Kubuqi and Maowusu desert (Figure 1). In particular, in the Buliangou mine located in the northern part of the coalfield, the ecological environment is more fragile, and the geological structure is more complex.

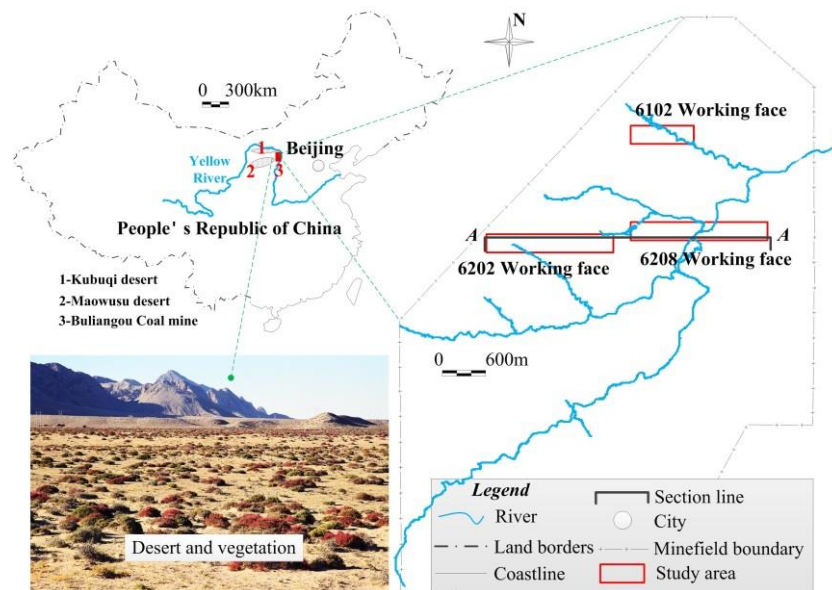


Figure 1. Location of Buliangou coal mine and its fragile ecological environment.

2.1. Overview of Buliangou Mine

The location of Buliangou mine is shown in Figure 1, covering an area of 33.2 km², with coal reserves of 1.09 billion tons. The surface of the mining area is covered by loess and aeolian sand. The altitude is 1127–1346 m, which gradually decreases from southwest to northeast. The Yellow River and several other rivers are distributed in the mine field or in the vicinity. In natural conditions, the above surface water level will change due to rainfall. However, due to the presence of red clay (Figure 2), the water level does not change much. These water sources can ensure the growth of plants, which is of great significance for preventing soil desertification. Therefore, protection of the integrity of the red-clay layer in the mining process is the focus of this article.

The Buliangou mine belongs to the Carboniferous and Permian coal fields. It is located in the northern part of the coal-rich depression in north China. The ancient geologic environment is close to the continental margin of Inner Mongolia. The Late Carboniferous paleogeographic environment was a delta alluvial plain, and the crust subsidence and the peat swamp accumulation maintained balance for a long time; therefore, the coal seam of the Taiyuan formation is very thick. However, the early Permian paleogeographic environment turned into a piedmont alluvial plain, and the peat swamp phase ended. Thus, the coal seam is smaller in the Shanxi formation. Only one earthquake occurred in history (1976), with a magnitude of 6.3, the epicenter of which was about 100 km away from the coal mine, and it did not have a significant impact on the study area.

Figure 2 shows the longitudinal section of the F6202 and F6208 working faces (the position of the section line is shown in Figure 1). From top to bottom, the coal seam roof mainly includes a sand layer, red clay, sandstone and mudstone interbeds, a thick sandstone layer with strong strength

(i.e., KS), and a thin fine sandstone and mudstone layer with less strength (i.e., immediate roof). The main mineable coal seam is 6# coal which belongs to the Carboniferous era, and its thickness is 5.6–16 m. The main KS and the inferior KS in the coal seam roof is thick and it belongs to the type of terrigenous alluvial plain dominated by continental facies [22]. Such geological conditions mean that the mechanical strength of the KS is high; however, once the KS breaks, it will cause large-scale ground settlement, and destroy the integrity of the red-clay layer. More seriously, the thickness and distribution of the coal seam and rock strata in the immediate roof and weakly consolidated strata are variable (Figure 2), which leads to the irregularity of the overlying strata movement and ground settlement.

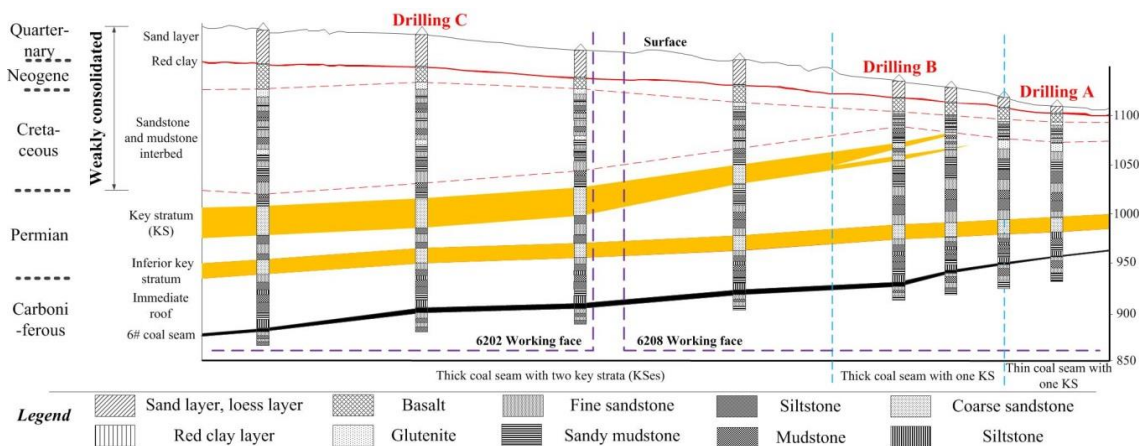


Figure 2. The longitudinal section of the F6202 and F6208 working faces.

The F6202 and F6208 working faces were selected as the study areas. The two faces penetrate the entire mine from east to west (Figure 1), and the diversified rock distribution conditions can represent the entire mine well. In order to facilitate similar simulation tests (see Section 3.1) and theoretical calculations (see Section 3.2) to study the mining influence on roof strata, the study area was divided into three parts according to the distribution characteristics of KS (the distinguishing method is shown in Section 3.2): a thick coal seam with two KS, a thick coal seam with one KS, and a thin coal seam with one KS. It should be noted that coal more than 5 m thick belongs to the classification of thick coal seam, while the “thin coal seam” mentioned in this article is only relatively speaking, because the thinnest coal seam thickness is 5.6 m.

2.2. Mining Consequences in F6102 Working Face

The consequences of coal seam excavation without protecting the KS are shocking. Taking the F6102 working face as an example (Figure 1), when the distance between the coal mining face and the cutting cut was 65 m, a square collapse pit appeared and gradually expanded into a circle with a diameter of 250 m and a depth of 15 m. In addition, with the mining advance, a more obvious step subsidence appeared on the surface, as shown in Figure 3. Complex geological factors are the fundamental causes for the formation of collapse pits according to Section 3. In the case of a thick coal seam with one KS, the separation space below the KS is large during the mining process, and the structure formed by breaking strata is not stable. Once the KS is broken, further instability of the structure will occur, which will lead to large-scale surface collapse.

Obviously, such surface deformation will destroy the integrity of red clay and bring about enormous ecological problems. This severe ground settlement is unacceptable for the F6202 and F6208 faces, as they both have mainstreams on the surface. The destruction of the red-clay layer will lead to coal mine water inrush accidents, and cause a drop in surface water levels. Separation grouting technology is an efficient and low-cost rock formation control technology; however, before using this method, we need to study the law of overlying strata under different strata distribution conditions.

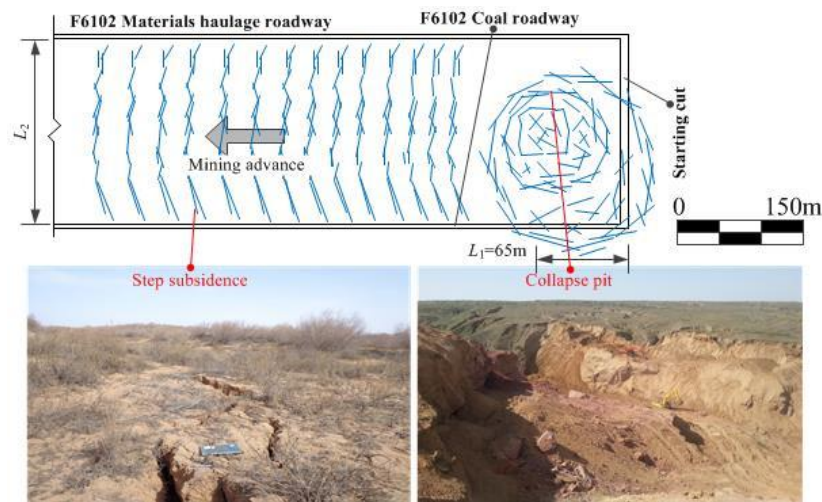


Figure 3. Schematic map of ground settlement.

The basic geological conditions of the study area are as follows: the average mining depth is 355 m, the coal seam thickness is 5.2–15.3 m, and the inclination angle is 0–7°. The long-wall retreat-type comprehensive mechanized caving method is used in each working face, and the length in the strike direction is 250 m ($L_2 = 250$ m). The lengths in the dip direction (i.e., L_1) of the two working faces are 1414 m and 2535 m, respectively.

3. Methods

Under the different thickness of coal seam, rock strata, and weakly consolidated strata, the movement of strata in the immediate roof and the range of separation space show different evolution rules. The uncertainty of the above rules will bring great challenges to the practice of separated strata grouting. Therefore, we applied similar simulation tests and theoretical calculations with good intuitiveness and reproducibility to analyze the overburden strata movement and range of separation space under the condition of varying thicknesses of strata.

3.1. Similar Simulation Tests

The use of similar simulation tests is widely applied to studying overburden movement during mining advances because of good visibility and repeatability. The basic method involves the use of some artificial material (single or mixed material) before establishing a similar model according to the similarity principle [23] and the parameters of the prototype (or the actual engineering geological conditions). The size of the similar model is mainly limited by the experimental equipment. The thickness of each rock stratum or coal seam in the model down-scales the size of the prototype. By observing the breaking form of the strata and the range of separation space on the similar model, we can deduce the law of overlying strata movement that may occur in the prototype.

Considering that the height of the experimental equipment was 140 cm and the mining depth was about 250 m (Point C in Figure 2), the similarity ratios could be determined as follows: (1) geometric similarity ratio, 1:200; (2) bulk density similarity ratio, 1:1.5; (3) stress and strength similarity ratio, 1:300; and (4) time similarity ratio, $1:200^{1/2}$. Materials such as river sand, gypsum, and calcium carbonate were chosen to simulate sedimentary rocks. Materials such as river sand, Vaseline, and loess were chosen to simulate red clay. Flaky mica was selected as a layered material between rock layers. According to the above ratio and mechanical parameters of roof strata determined from drilling data, the mix proportion of various materials could be reversed based on the relevant literature [23–26]. The results are shown in Table 1.

Table 1. Mix proportion of similar materials.

Lithology	Material and Mixing Ratio					Rock Mechanical Parameters under Natural Conditions		
	River Sand	Gypsum	Calcium Carbonate	Vaseline	Loess	Elastic Modulus (GPa)	Body Force (KN·m ⁻³)	Tensile Strength (MPa)
Soil	7.2	0.4	1	-	-	1.5	17	-
Sand	10.0	0.4	1	-	-	3.0	18	-
Red clay	0.5	-	-	0.1	1	2.2	20	-
Basalt	7.1	0.5	1	-	-	20.4	25	-
Glutenite	8.5	0.4	1	-	-	31.2	25	2.1
Sandy mudstone	9.9	0.4	1	-	-	17.2	25	1.7
Coarse sandstone	14.3	1	1	-	-	28.5	25	3.8
Fine sandstone	10.5	0.5	1	-	-	20.2	25	-
Siltstone	9.3	0.3	1	-	-	17.6	25	-
Carbon mudstone	8.5	0.4	1	-	-	16.1	25	-
Coal	9.8	0.4	1	-	-	1.03	18	-
Mudstone	8.2	0.5	1	-	-	19.2	25	-

According to the three typical geological conditions (points A, B, and C shown in Figure 2), three similar models were established. In the process of the tests, the coal seam was excavated from 20 cm to the left boundary, and then advanced from left to right with a speed of 10 cm/h. As mentioned above, the range of the separation space has a great impact on the separated strata grouting; therefore, the test results of the distance of mining face at $L_1 = 60\text{--}70\text{ cm}$ were selected for analysis, as shown in Figure 4. At this time, the range of separation space reached its maximum. The structure formed by broken strata in the immediate roof and the range of the separation space below the KS (s and d in Figure 4) are analyzed next.

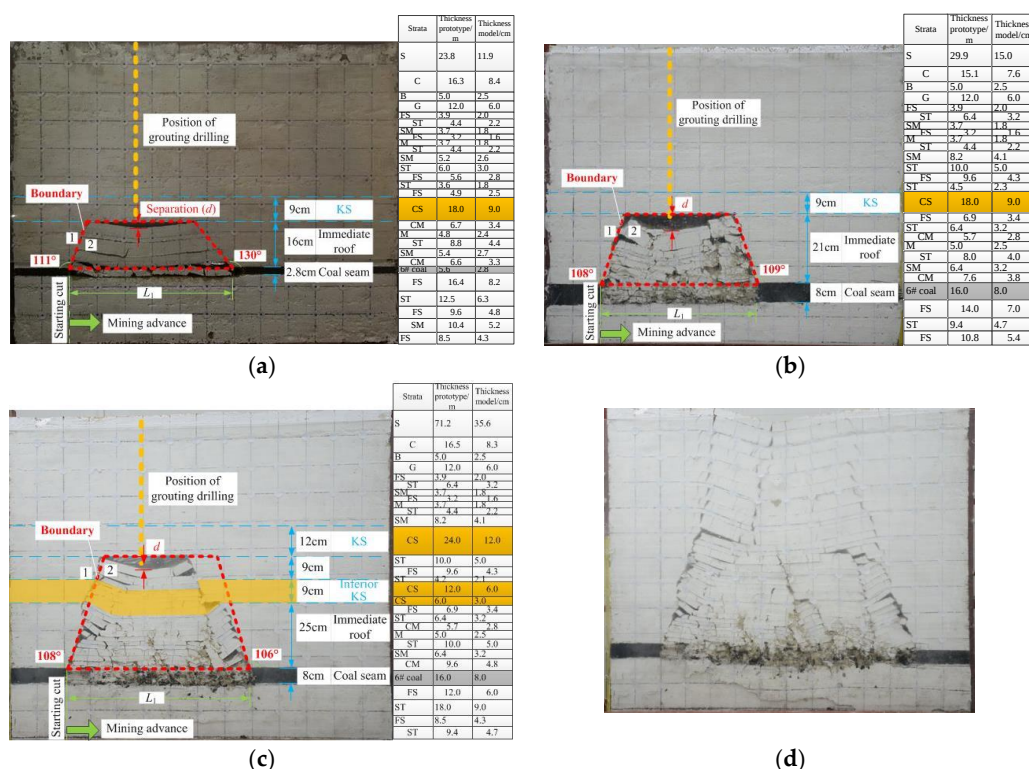


Figure 4. Results of similar simulation experiments (the size of the square lattice is 10 cm × 10 cm). (a) Thin coal seam with one key stratum (KS); (b) thick coal seam with one KS; (c) thick coal seam with two KS; (d) ground settlement (a case of two KSes). 1—short cantilever beam; 2—broken rock beam (or simply supported beam); S—sand layer; C—red clay; B—basalt, G—glutenite; FS—fine sandstone; ST—siltstone; SM—sandy mudstone; M—mudstone; CS—coarse sandstone; CM—carbon mudstone.

3.1.1. Structure Formed by Broken Strata

The structure formed by broken strata in the immediate roof determined the range of the separation space. At the same time, the structure was also the basis of theoretical calculation. However, the type of structure strongly depends on the number of KS, and the thickness of the strata and coal seam.

For the thin coal seam with one KS (Figure 4a), the roof did not collapse until $L_1 = 25$ cm. At this time, the middle part of the strata near the coal seam was bent and vertical cracks appeared, while inclined fissures inclined to the goaf appeared at both ends of rock strata. With the mining advance, the immediate roof collapsed, and then formed a loose rubble pile ($L_1 = 60$ cm). At this time, a cantilever beam was formed at the edge of the goaf and supported the left end of the broken rock strata below the KS, while its right end was supported by the rubble pile, forming a classic “voussoir beam” structure [8].

In contrast, under thick coal seam conditions, stable structures could not formed at the outset. For the thick coal seam with one KS (Figure 4b), when $20\text{ cm} < L_1 < 40\text{ cm}$, roof caving was similar to that of the thin coal seam condition. However, as the coal seam was too thick, the height of the rubble pile in the goaf was too small to form a stable structure. With the mining advance, the thick rock stratum in the upper part of the immediate roof collapsed. At this time, the cantilever beam (“1” in Figure 4b) gradually extended to the goaf, which meant that the span of the thick rock beam was small. Additionally, the rubble pile at the lower part of the rock beam was further broken; finally, a new structure of “high-position cantilever beam/simply supported beam” was formed.

For the case of the thick coal seam with two KS, a composite structure (Figure 4c) similar to that of Figure 4b was formed. However, this structure was more stable due to the expansion of the broken effect caused by the breaking of inferior key strata.

3.1.2. Range of Strata Separation under the KS

The range of the separation space under the KS (i.e., parameters d and s in Figure 4) will have a significant impact on the stability of the KS. For the horizontal range of the separation space (i.e., s in Figure 4), it can be determined from two envelope curves: (1) at the left boundary, the separation space is always within a 79° oblique line regardless of the thickness of the coal seam; (2) at the right boundary, under the condition of a thin coal seam, the separation space is within a 60° oblique line, while the separation space is within an 84° oblique line in the thick coal seam conditions (Figure 4).

Figure 5 reflects the relationship between the vertical range of the separation space (i.e., d in Figure 4) and the distance of the mining advance (i.e., L_1 in Figure 4). Two results could be obtained. Firstly, the value of d is closely related to geological conditions. Comparing the three curves, we know that d initially increased and then decreased with the increase of L_1 under the three geological conditions. However, the maximum d ($d_{\max} = 2.2$ cm) under thin coal seam conditions was much smaller than that under thick seam conditions. Furthermore, the maximum d ($d_{\max} = 5.8$ cm) under thick seam conditions with two KS was smaller than that under one KS condition ($d_{\max} = 7.9$ cm). Secondly, the starting position of the separation space (L_{1s}) and the position of the $d_{\max}$ (L_{1m}) are also affected by geological factors. Under the condition of a thick coal seam with one KS, the starting position of the separation space ($L_{1s} = 40$ cm) was smaller than that of the other two geological conditions ($L_{1s} = 50$ cm). At the same time, $L_{1m} = 55$ cm under the condition of the thick coal seam with one KS was smaller than that in the other two geological conditions ($L_{1m} \approx 60$ cm). The above two laws show that, under the geological conditions of a thick coal seam with one KS, special attention should be paid to the timing of the separation grouting operation.

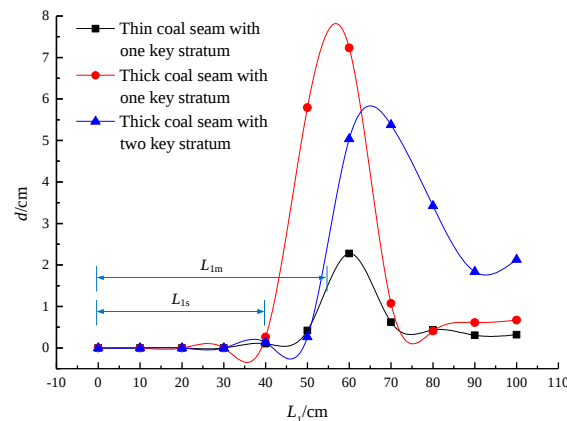


Figure 5. Evolutionary law of the vertical range of separation space with distance of mining advance.

3.2. Theoretical Calculations

The evolutionary law of separation space under three typical geological conditions (Points A, B, and C in Figure 2) could be obtained using similar simulation tests. However, a few experiments were obviously insufficient for diversified formation thickness. Therefore, theoretical calculation was necessary.

3.2.1. Equations for Geometric Parameters of Separation Space

The geometric parameters of separation space include two aspects. The first is the vertical position (h_0 in Figure 6) of separation space; the grouting layer is located below the KS, as described above. Therefore, the essence of this problem is to determine the location of the KS. The second is the range of separation space. The horizontal and vertical ranges are closely related to the breaking form of the immediate roof strata and the breaking span of the KS, and these parameters can be obtained from the block mechanics.

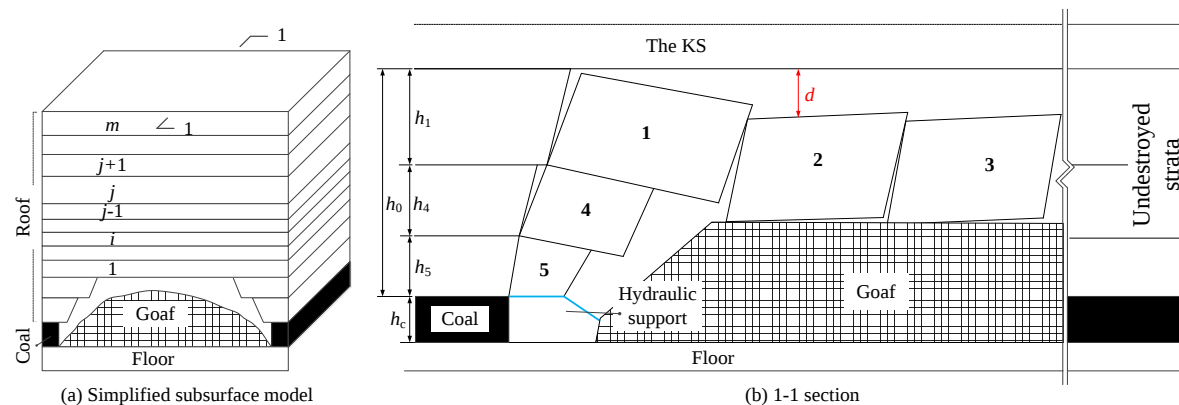


Figure 6. Calculation model for location of KS.

Based on the three hypotheses, including the horizontal distribution of strata, and the uniform and isotropic rock masses, and ignoring tectonic stress, we established the analytical model shown in Figure 6 combined the similar simulation results. The geometric parameters (h_0 , s , and d) of separation space could be obtained using the three steps below.

(1) The KS can be determined by analyzing the stiffness and strength of each rock stratum from bottom to top. As shown in Figure 6a, if the deflection of the stratum (labeled “ j ”) is less than that of the lower strata (labeled “ $1 \sim j - 1$ ”), upon controlling the deformation of its upper strata (labeled “ $j + 1 \sim m$ ”), then the stratum “ j ” can be generally judged as the KS. At this time, the weight of

" $i + 1 \sim j$ " strata acting on stratum " i " (i.e., $q_i^{(j)}$) will be less than that of " $i + 1 \sim j - 1$ " strata acting on stratum " i " (i.e., $q_i^{(j-1)}$). The mathematical expression is as follows [27]:

$$q_i^{(j)} < q_i^{(j-1)}, \quad (1)$$

where $q_i^{(j)} = E_i h_i^3 \cdot \left(\sum_{j=i}^m \gamma_{j-1} h_{j-1} + q_j \right) / \sum_{j=i}^m E_j h_j^3$, and $q_i^{(j-1)} = E_i h_i^3 \cdot \sum_{j=i}^m \gamma_{j-1} h_{j-1} / \sum_{j=i}^m E_{j-1} h_{j-1}^3$.

Here, m is the total number of strata, h_i is the thickness of each stratum (m), γ_i is bulk force (N/m²) when the width of the rock beam is 1 m, E_i is the elastic modulus (Pa), and q_j is the self-weight of the " $j + 1$ " stratum (N/m).

In addition to Equation (1), the KS also needs to meet the following strength conditions:

$$s_j > s_{j-1} \geq s_{j-2} \geq s_{j-3} \cdots, \quad (2)$$

where s_j , s_{j-1} , s_{j-2} , and s_{j-3} are the initial breaking spans of rock stratum of j , $j - 1$, and $j - 2$. The expression indicates that the breaking span of the KS is larger than that of other strata below the KS.

(2) The range of separation space in the horizontal direction is affected by the breaking span of the KS. According to the similar simulation test results (Section 3.1), we know that the breaking process of rock strata is from a fixed-fixed beam into a simply supported beam; thus, Equation (2) can be used to calculate s_i .

$$s_i = h_i \sqrt{2\sigma_{Ti} / q_i^{(j-1)}}, \quad (3)$$

$$s_i = h_i \sqrt{\sigma_{Ti} / (3q_i^{(j-1)})}, \quad (4)$$

where σ_{Ti} is the tensile strength of stratum " i " (Pa).

(3) The range of separation space in the vertical direction (i.e., d in Figure 4) can be obtained using the method described here. The calculation model shown in Figure 6 is applicable to the three typical geological conditions shown in Figure 2. Considering that the geological conditions of the "thick coal seam with two KS" are more widely distributed in the study area, this article takes this geological condition as an example for the analysis. For the case of one KS, the results can be obtained by reducing the load on the KS, because the mining depth in the area with one KS is lower than that in the area with two KS.

Assuming that the gangue below the rock mass 2 is compacted, d can be obtained using the following geometric relationship:

$$d = h_c - (c_f - 1) \cdot (h_4 + h_5), \quad (5)$$

where h_n ($n = 1-5$) represents the thickness of strata where the rock n is located (m), h_c is the thickness of the coal seam, and c_f is the coefficient of thermal expansion. The relationship between c_f and h_0 ($h_0 = h_1 + h_4 + h_5$) can be obtained from field-measured data, $c_f = 1.30655h^{-0.058745}$ (one KS condition), and $c_f = 1.30655h^{-0.046742}$ (two KS condition). Thus, the range of the separation in the vertical direction can be obtained.

3.2.2. Evolutionary Law of Separation Range

Relatively speaking, the distribution of the KS is relatively stable on the whole, and the change in range of the thickness of inferior KS is less than 2 m, while that of the main KS is less than 3 m in the area of two KS shown in Figure 2. This means that h_0 (Figure 6) is deterministic. However, the thickness variations of the coal seam (5.6–16 m), the strata (12–78 m) below the KS, and the loose layer (30–208 m) are large. That is to say, s and d (Figure 4) will change along with the changes of these parameters,

and their evolutions can be calculated using Equations (1) to (5) and the engineering parameters shown in Table 1; the results are shown below.

Figure 7 shows the evolutionary law of s with R_h and h_L under the different numbers of KS. In general, s is greatly affected by h_L and R_h . In the case of one KS, when R_h increases from 0.1 to 10 (i.e., the rock thickness increases and the soil thickness decreases), s decreases from 42 m to 30 m ($h_L = 160$ m), from 57 m to 42 m ($h_L = 120$ m), and from 82 m to 65 m ($h_L = 80$ m). At the same time, as h_L increases from 80 m to 200 m, s decreases rapidly from 72 m to 26 m ($R_h = 1$). The evolutionary law of s with R_h and h_L under the two KS conditions is basically the same as that under the one KS condition. However, R_h has a smaller effect on s in the two KS condition; specifically, when R_h increases from 0.1 to 10, s decreases from 45 m to 38 m ($h_L = 100$ m). Moreover, h_L has a smaller influence on s under two KS; when h_L is reduced from 140 m to 30 m, L increases from 33 m to 70 m ($R_h = 1$).

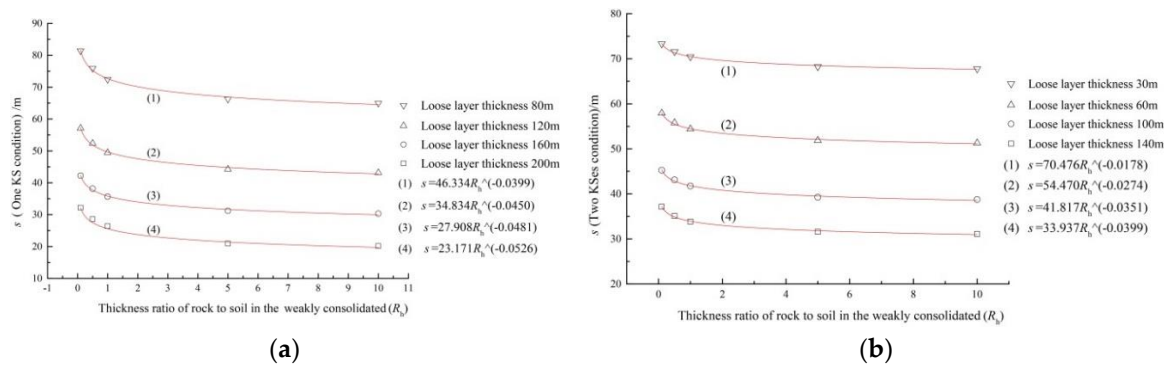


Figure 7. Evolution of the horizontal range of separation space (s) with thickness ratio of rock to soil (R_h) in different loose-layer thicknesses (h_L): (a) one KS condition; (b) two KS condition.

Figure 8 shows the effect of h_c and h_0 on d . The similarity between the two figures is that when h_0 is constant, d increases linearly with the increase of h_c , no matter what the number of KS is. Moreover, when h_0 increased from 10 m to 70 m (one KS condition), or from 10 m to 80 m (two KS condition), the slope of the straight line in Figure 8 increased, which means that the larger the thickness of the immediate roof is, the more sensitive the vertical separation range will be with the thickness of the coal seam.

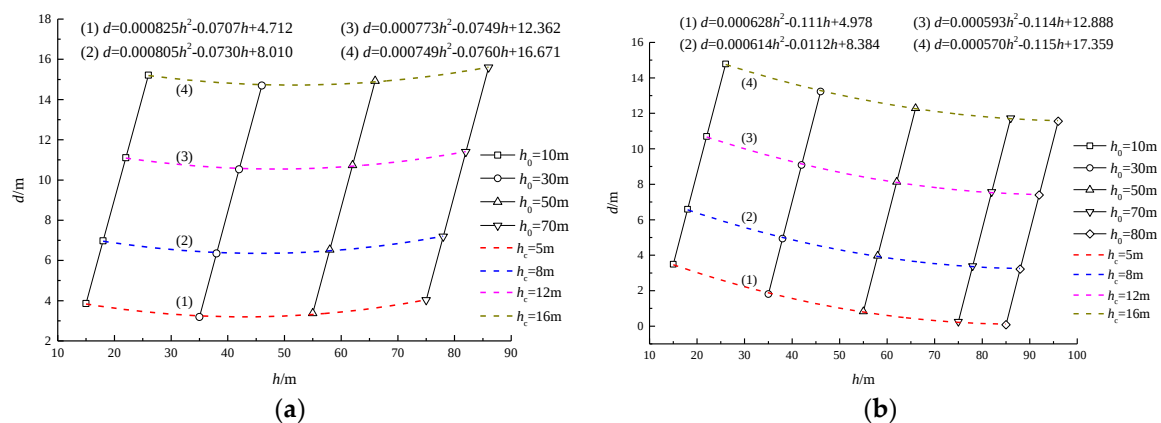


Figure 8. Evolution of the vertical range of separation space (d) with thickness of coal seam (h_c) and immediate roof (h_0): (a) one KS condition; (b) two KS condition.

The differences between the two geological conditions are described here. For one KS condition, with the increase of h_0 from 10 m to 70 m, the evolution of d decreased first and then increased in a parabolic form. The minimum value of d was 3.2 m (e.g., $h_c = 5$ m), which appeared at the position of $h = 45$ m ($h = h_c + h_0$), and the maximum value was 4.0 m, which appeared at $h = 75$ m. For the two KS

condition, we still took “ $h_c = 5$ m” as an example for analysis. With the increase of h_0 from 10 m to 80 m, the evolution of d decreased in a parabolic form. However, d had a monotonous decreasing trend with h_c , and the minimum value of d (0.08 m) appeared at the position of $h = 85$ m, and the maximum value of d (3.49 m) appeared at $h = 5$ m. The above data show that, under the condition of one KS, the grouting amount will first decrease and then increase along with the thickness of immediate roof. Under the condition of two KS, the grouting amount continues decreasing with the increase of immediate roof thickness.

The theoretical calculation model can be verified using similar simulation tests with the same parameters as the latter. One test involved the condition of one KS, $h_L = 80$ m, $R_h = 0.05$, and $h_c = 5.6$ m and $h_0 = 32$ m (thin coal seam), or $h_c = 16$ m and $h_0 = 32$ m (thick coal seam). The second test involved the condition of two KS, $h_L = 30$ m, $R_h = 0.05$, $h_c = 16$ m, and $h_0 = 86$ m. Then, we calculated the horizontal range of the separation space in the above three cases ($s = 81$ m, $s = 81$ m, and $s = 72$ m), and the similar simulation results were determined as 80 m, 84 m, and 76 m, respectively. The calculation results of the vertical range of the separation space were $d = 4.1$ m, $d = 13.9$ m, and $d = 11.2$ m, and the similar simulation results were 4.4 m, 15 m, and 10.8 m, respectively. The difference between the calculated results and the experimental results was small; thus, the theoretical calculation model and mathematical expression were reasonable.

4. Grouting Scheme, Results, and Discussion

The basic principle of the separated strata grouting technology is that the main separation space is formed below the KS during mining advance. The filling material is injected into the space through surface drillings to provide support for the KS (Figure 4), thus ensuring the integrity of the KS and reducing ground settlement. Based on the parameters of the location and size of the separation space (Section 3), we implemented the separated strata grouting and corrected the grouting parameters according to the on-site data monitoring.

4.1. Practice and Results of Separated Strata Grouting

Considering that the overburden strata movement is the most intense under the geological conditions of thick coal seam with one KS (Figure 4), we took the range of $0 \text{ m} < L_1 < 200$ m in the F6202 working face as a test section to verify the effect of separated strata grouting.

Based on the results of Section 3 and the practice of separated strata grouting under similar engineering geological conditions [28], the grouting parameters can be defined according to the following methods: the grouting layers are located below the KS, and the grouting boreholes are generally located near the maximum breaking span of the KS. The horizontal range of the separation space (s) can be obtained from the fitting equation shown in Figure 7. Combining the above s data and the results of the separation space position shown in Figure 4, the distance from the grouting borehole to the starting cut can be obtained (marked L_1'). The location of grouting boreholes needs to be adjusted according to specific geological conditions, such as the thickness of weakly consolidated strata and the thickness ratio of rock to soil in the weakly consolidated layer. The grouting parameters are shown in Table 2.

Table 2. Parameters of separated strata grouting.

Drilling Position	Grouting Pressure	Grouting Material
$L_1' = 82$ m, 143 m, 186 m	2.8 MPa	Mixture of water, loess, and fly ash

In addition to the above grouting parameters, the data of the pressure on hydraulic support (pressure acting on hydraulic support due to rock pressure) and grout amount are also needed to adjust the speed of mining advance in time to ensure that the cavity in the separation space is fully filled. The curves of the above two parameters along with the mining advance are shown in Figures 9 and 10.

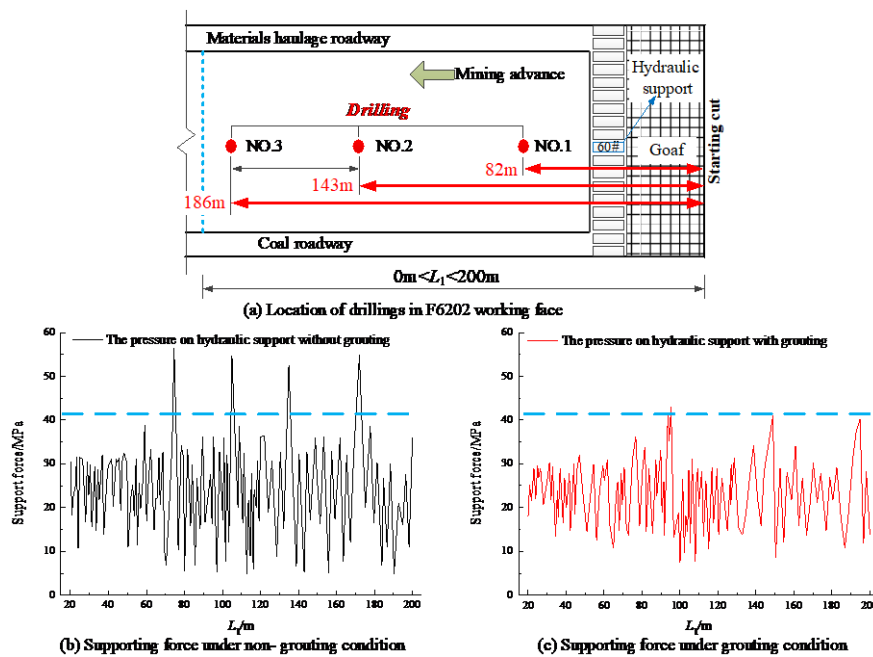


Figure 9. Real-time monitoring results of hydraulic support's support force under grouting and non-grouting conditions (once the support force exceeds the blue line, the KS breaks).

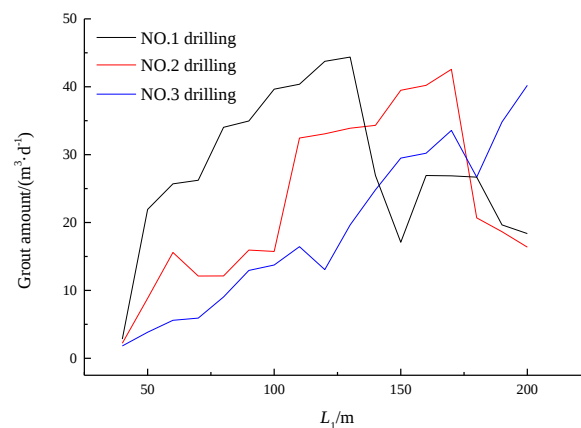


Figure 10. Variation law of grout amount.

Figure 9 shows that the separated grouting operation can greatly reduce the peak pressure on the hydraulic support (from 56 MPa to 43 MPa) and delay the generation of peak pressure (L_1 increased from 74 m to 86 m). This result is basically consistent with the drilling location shown in Table 2, which shows the rationality of drilling arrangement. Figure 10 shows that the position of working face has great influence on grout amount. Taking the data of NO. 1 drilling as an example, when $L_1 = 40$ m, the grout amount began increasing rapidly. With the immediate roof collapsing section by section, the grout amount rose step by step. When $L_1 = 80$ m, the grout amount increased fastest. When $80\text{ m} < L_1 < 130\text{ m}$, the grouting rate gradually decreased and reached its peak at $L_1 = 130\text{ m}$. Thereafter, with the flexural deformation of the KS, the grout amount of the NO. 1 borehole began decreasing. However, with the continued collapse of the adjacent roof, the grout amount of the NO. 1 grouting hole picked up again.

According to the data shown in Figures 9 and 10, when $L_1 = 98\text{ m}$, the pressure of hydraulic support increased rapidly, and the grout amount also increased. This phenomenon shows that, when the rock pressure is obvious, the slurry is not full of the separation space; thus, the overlying strata will have a significant impact on the KS. According to the results of similar simulation tests, the periodic collapse span of the KS was about 20 m (horizontal direction), and the maximum grout

amount occurred at $L_1 = 125$ m. Therefore, the advancing speed of the working face was reduced from 4 m/d to 3.2 m/d to ensure that the separation space was filled with grout. The speed was adjusted according to the real-time feedback data of Figures 9 and 10, and the results of surface subsidence reduction are shown in Figure 11.

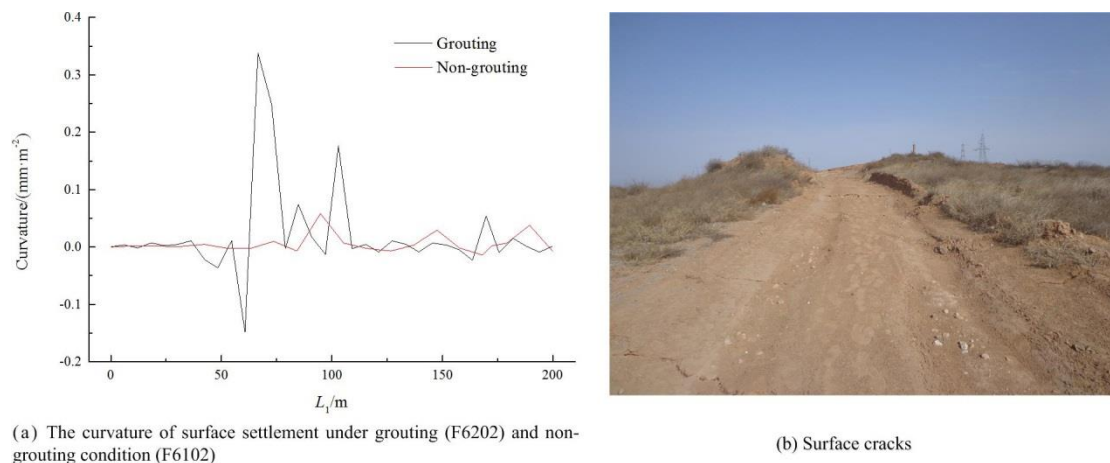


Figure 11. The results of separated strata grouting.

Figure 11 shows that the KS is supported by the stone body after grout solidification, making the structure formed by the broken strata more stable. Therefore, the absolute value and curvature of ground settlement will be more relaxed. In fact, the observation data of surface movement show that the ground settlement of the grouting working face was about 52% of that of non-grouting face, while the surface deformation curvature of the former was only 6.7% of that of the latter (Figure 11). The above data indicate that the ground settlement sunk as a whole, but the integrity of the red-clay layer was largely maintained. The above analysis shows that the grouting parameters shown in Table 2 can meet the requirements of protecting surface water resources.

4.2. Discussion

In this article, separated strata grouting technology was used in Buliangou mine located in arid or semi-arid areas to prevent surface water loss and soil desertification. As a key factor in the success of grouting, the evolutionary laws of separation space under complicated geological conditions are obtained using a series of methods, including similar simulation tests, theoretical calculations, and monitoring of pressure on hydraulic support and grouting amount in the process of in situ tests. The test results demonstrate that the number of KS, the proportion of rock in loose strata, and the thickness of the coal seam, immediate roof, and loose bed will have a significant impact on the size and location of separation space, thereby influencing the effect of grouting. This finding is significant because it clearly shows the geological conditions in the event of maximum uneven settlement (Figure 3), including one KS, thick coal seam, thin immediate roof, thick loose bed, and large proportion of rock in loose bed. At this time, the separation space is the largest, and the KS without support will break and affect the integrity of red clay after large-scale collapse, resulting in the loss of surface water resources. To our knowledge, the range evolution of the separation space is proposed herein for the first time considering the strata distribution. In the case of deep-buried and thin coal seams, the continuum mechanics method was used previously for predicting the stress, deformation, and fracture properties of the KS when the strata are uniformly distributed [6,7,9,29]. However, the grouting parameters of Buliangou mine cannot be concluded from that approach because it was conducted with a lack of consideration of the research object (many articles regard the KS as the research object rather than the separation space) [8], a lack of consideration of the continuum mechanics method not being suitable for broken strata [11], a lack of consideration of

strata distribution, and especially a lack of consideration of the number of KS [30]. On the other hand, the methods shown in this article, including similar simulation tests with three typical geological conditions, and theoretical calculations based on a new model with various strata thickness conditions, make the results more meaningful.

To date, most researchers used “backfill mining” or “strip mining” for reducing the absolute value of ground settlement [31,32]. However, the disadvantages of high cost, complex filling process, or low recovery ratio make these technologies not the best option. Although a layer separation method aimed at reducing the absolute value of ground settlement was reported in a previous study [28], the influence of the variation of the strata thickness on the separation space or on the grouting parameters was still not considered. Based on similar simulation tests and theoretical analysis data, separated strata grouting technology considering complex geological conditions was adopted herein. The grouting parameters were adjusted in time based on feedback from the in situ test, such that the relative value (or curvature) of ground settlement was significantly reduced. Through the above method, we protected the integrity of the red-clay layer under complex geological conditions (Figure 12), thereby protecting the surface water resources.

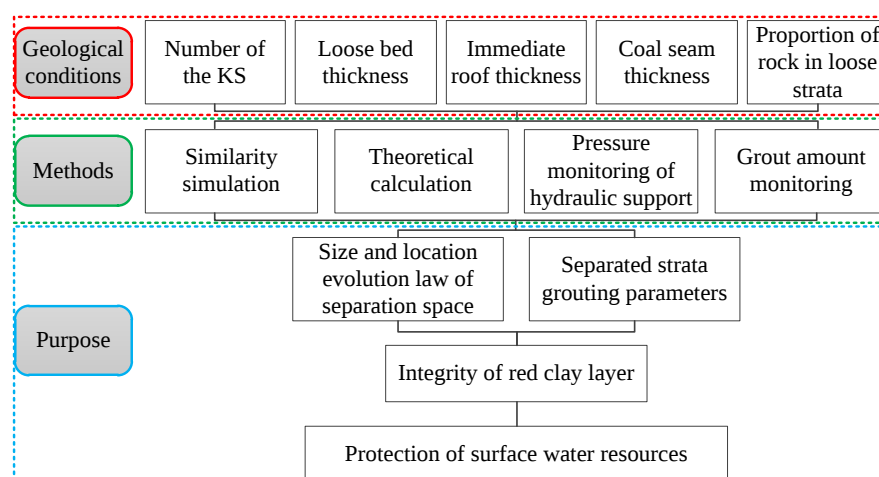


Figure 12. Research methods and considerations of surface water protection under mining influence.

5. Conclusions

The main conclusions drawn from the investigations are summarized as follows:

(1) The number of KS has a significant impact on the structure of the broken strata under the KS. Under the mining influence, the broken strata form a stable “voussoir beam” structure in the case of a thin coal seam with one KS. In case of a thick coal seam, the broken strata form an unstable structure of “high position cantilever beam/simply supported beam”. Once the KS breaks, the structure will further destabilize, leading to the occurrence of surface collapse pits, especially for one KS condition.

(2) The strata distribution plays a crucial role in the range of separation space. Regardless of the number of KS (one or two), the horizontal range of the space decreases with the increase of the loose layer thickness, or the increase of thickness ratio of rock to soil in the loose layer. The vertical range of the space increases with the increase of coal seam thickness, initially decreases and then increases with the increase of the strata thickness below the KS in one KS condition, and decreases with the increase of the strata thickness below the KS in two KS condition.

(3) The data from the in situ test are important for determining grouting parameters. Through the real-time feedback data of the grout amount and pressure on hydraulic support, the location of the drilling hole was determined, and the speed of mining advance was adjusted in time. The grouting practice showed that the curvature of ground settlement was effectively controlled, which protects the integrity of the red-clay layer and, thus, protects the surface water resources.

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