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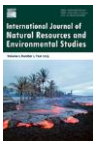

Study on Overburden Failure and Surface Sinkhole Development Law during Extra-Thick Coal Seam Mining beneath Thick Unconsolidated Layers

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ABSTRACT

To address the problem of surface collapse and sinkhole disasters induced by fully mechanized top-coal caving mining of extra-thick coal seams beneath thick unconsolidated layers, the F6204 working face of Buliangou Coal Mine was selected as the engineering background. Field investigation, theoretical analysis, and numerical simulation were employed to investigate the evolution characteristics of overburden failure and the formation mechanism of surface sinkholes. The results indicate that the overburden structure of the F6204 working face is mainly composed of a “loess layer–conglomerate–basalt” assemblage, in which the basalt stratum acts as the primary key stratum. After coal extraction, a distinct “three-zone” overburden structure is formed. With the increase in mining thickness, the stability of the beam-arch structure in the overburden gradually decreases. Once the basalt primary key stratum fractures, surface collapse and sinkhole disasters are likely to occur. When the coal seam thickness exceeds 15 m, surface deformation gradually transforms from continuous subsidence to discontinuous stepped collapse. Based on these findings, a control technology combining high-level key stratum presplitting and separation-layer grouting is proposed, which can effectively mitigate surface sinkhole hazards. The research results can provide a reference for the safe and efficient mining of extra-thick coal seams under similar geological conditions.

KEYWORDS

Thick Unconsolidated Layer; Extra-Thick Coal Seam; Overburden Failure; Surface Sinkhole Collapse.

1. INTRODUCTION

In recent years, with the continuous growth of China’s energy demand, large-scale coal bases in the western regions have entered a stage of high-intensity mining. Vast resources of extra-thick coal seams are distributed in regions such as Inner Mongolia, Shaanxi, and Xinjiang, where fully mechanized top-coal caving (FMTC) mining technology has been widely applied due to its high resource recovery rate and production efficiency. However, under high-extraction and high-mining conditions of extra-thick coal seams, overburden displacement is intense, which can easily trigger water-conducting fracture penetration, surface crack propagation, and sinkhole collapse hazards, particularly in areas covered by thick unconsolidated layers.

Thick unconsolidated layers are characterized by loose structure, low shear strength, and poor stability. Once the underlying bedrock experiences large-scale instability, these layers are prone to sudden collapse, resulting in funnel-shaped sinkholes[1]. Such sinkhole hazards not only damage the surface ecological environment but may also lead to structural damage, ventilation disorder, and abnormal gas outbursts in the mine, posing a serious threat to safe production. Therefore, investigating the overburden failure behavior of extra-thick coal seams beneath thick unconsolidated layers and the formation mechanism of surface sinkholes has significant engineering importance.

Extensive research has been conducted internationally and domestically on overburden structural evolution, key stratum control, and surface subsidence patterns in extra-thick coal seam mining. Qian Minggao et al.[2] proposed the key stratum theory, providing a theoretical foundation for overburden movement analysis. Jiang Fuxing et al.[3] established the “O-X” overburden structure model for FMTC mining, and Guo Wenbing et al.[4] investigated the evolution of surface cracks under thick unconsolidated layers. Nevertheless, most existing studies focus on general subsidence patterns, and systematic research on the formation mechanisms of surface sinkholes and the collaborative failure of key strata under thick unconsolidated layers remains limited.

Based on this background, the present study takes the F6204 working face of Buliangou Coal Mine as the research object. By integrating site geological conditions and numerical simulation results, this study analyzes the evolution of overburden structures and the formation mechanism of surface sinkholes, and proposes targeted disaster-control measures. As high-intensity coal exploitation in western China continues, the scale of FMTC mining of extra-thick coal seams is expanding. Under thick unconsolidated layer coverage, the complex overburden structure and strong mining-induced disturbances easily lead to surface cracks, stepped subsidence, and sinkhole collapse, posing severe risks to mine safety and the ecological environment[5]. Although previous studies have investigated the development of the “three-zone” overburden structure and key stratum control mechanisms, the formation mechanisms of sinkholes and the failure characteristics of key strata under thick unconsolidated layers are still not well understood. Therefore, further research is necessary to provide theoretical guidance for hazard prevention and control.

2. GEOLOGICAL CONDITIONS

2.1. Working Face Overview

The Buliangou Coal Mine is located in Dalu Town, Zhungeer Banner, Ordos City, Inner Mongolia Autonomous Region. The F6204 working face primarily exploits the 6# coal seam of the Taiyuan Formation, Upper Carboniferous. The working face is characterized by an asymmetric topography, with higher elevations in the west and lower areas in the east, and a central depression. Surface undulations are pronounced, and the entire area is covered by Quaternary loess, with thickness varying according to topographic relief. Vegetation cover is sparse, and soil erosion is widespread. The eastern boundary of the working face directly connects to the 6# coal intake airway, the north adjoins the F6203 working face, the western boundary coincides with the mine field boundary, and the southern area remains unmined 6# coal.The working face has an average burial depth of 420 m, a strike length of 1,330 m, a dip length of 240 m, and a total area of 319,551 m^2. The coal seam has an average thickness of 15.5 m, with dip angles ranging from 1° to 9° (average 5°). Mining is conducted using a strike-longwall retreat method with fully mechanized top-coal caving, and the roof is managed by the complete caving method. The layout of the F6204 working face is illustrated in Figure 1.

Based on the geological survey data of Buliangou Coal Mine and the borehole detection data of the F6204 face, the overall overburden structure of the F6204 working face is clarified.

The uppermost overburden consists of a Quaternary unconsolidated layer, whose thickness varies significantly with topographic relief, ranging approximately from 15 to 84.55 m, with an average of 54.09 m. This layer is primarily composed of silty loess and silty clay, locally interbedded with minor sand-gravel deposits. The layer exhibits extremely poor cementation, loose structure, high porosity

(35–45%), low shear strength, and is prone to softening and collapse upon water infiltration, providing negligible engineering stability.

The middle to upper overburden is predominantly composed of conglomerate, basalt, sandy mudstone, and coarse sandstone, with considerable thickness and relatively uniform distribution. The basalt stratum has an approximate thickness of 23 m, while the cumulative thickness of conglomerate reaches about 152.4 m, characterized by good integrity and high load-bearing capacity. Beneath the coarse sandstone, the strata sequentially consist of fine sandstone, sandy mudstone, medium sandstone, coarse sandstone, and carbonaceous mudstone.The 6# coal seam exploited at the F6204 working face has an average thickness of approximately 15 m, with a complex structure containing multiple interlayers of gangue.

The immediate floor consists of mudstone with a thickness of 8–25 m (average ~18 m), underlain by older strata of fine and medium sandstone with a total thickness of 30–50 m (average ~40 m). The integrated geological column is shown in Figure 2.

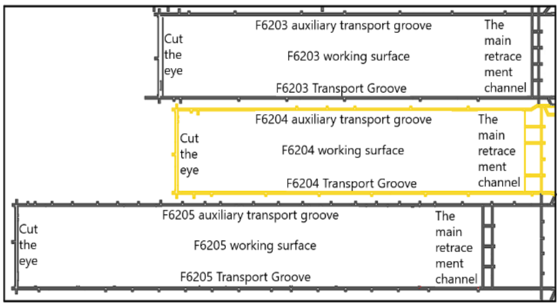
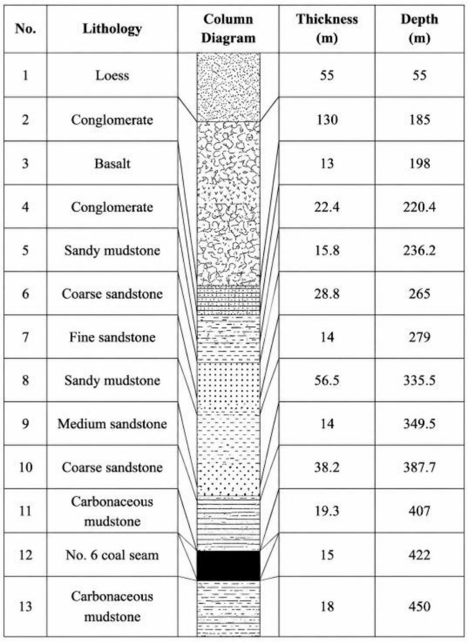


Figure 1. F6204 work face layout needs to be optimized



No.	Lithology	Column Diagram	Thickness (m)	Depth (m)
1	Loess		55	55
2	Conglomerate		130	185
3	Basalt		13	198
4	Conglomerate		22.4	220.4
5	Sandy mudstone		15.8	236.2
6	Coarse sandstone		28.8	265
7	Fine sandstone		14	279
8	Sandy mudstone		56.5	335.5
9	Medium sandstone		14	349.5
10	Coarse sandstone		38.2	387.7
11	Carbonaceous mudstone		19.3	407
12	No. 6 coal seam		15	422
13	Carbonaceous mudstone		18	450

Figure 2. F6204 working face overburden geological histogram

Laboratory rock mechanics tests were conducted to determine the physical and mechanical parameters of the overburden. Results indicate that the basalt exhibits the highest compressive strength, up to 95 MPa, while the loess layer has a compressive strength of only 5 MPa, demonstrating significant strength contrasts. Such differences among strata lead to pronounced layered deformation during mining: weak layers deform first through compression and separation, whereas hard layers form large-span cantilever structures that control the stability of the working face.

2.2. Surface Damage Characteristics

The 6# coal seam at the F6204 working face of Buliangou Coal Mine is a typical extra-thick coal seam, mined using fully mechanized top-coal caving (FMTC) technology. The large single-pass extraction thickness induces intense overburden fracturing, caving, and displacement under mining-induced stress, which in turn leads to significant surface deformation. To accurately characterize surface movement and deformation patterns and clarify the relationship between mining-induced overburden activity and surface damage, field measurements were conducted through the deployment of monitoring points and on-site surveys. The results indicate that, except for localized variations caused by topography and overburden heterogeneity, the surface above the goaf exhibits pronounced movement and deformation, characterized by significant discontinuity and large-magnitude displacement. During the extraction of the F6204 working face, surface damage primarily manifests in three forms:

(1) Surface Cracks: Cracks mainly occur along the boundaries of the goaf and near gully slopes, with widths generally ranging from 5 to 30 cm; some cracks penetrate deeper than 5 m.

(2) Stepped Subsidence: The central part of the goaf exhibits clear height differences, with step displacements ranging from 0.3 to 2.0 m.

(3) Collapse Sinkholes: Funnel-shaped collapse pits develop locally, with depths exceeding 30 m and maximum diameters exceeding 100 m.

3. NUMERICAL SIMULATION ANALYSIS

3.1. Numerical Model Setup

In this study, the Universal Distinct Element Code (UDEC) discrete element method was employed to simulate overburden failure and fracture propagation in extra-thick coal seam FMTC mining. The simulation captures the development of the caving zone, fracture zone, and bending subsidence zone (the "three-zone" system) above the goaf, illustrating the expansion pathways and connectivity of the fracture network.

The model domain was defined to include the main overburden strata from the surface down to the coal seam, as well as part of the underlying floor strata, in order to analyze roof-layer displacement and surface deformation. The model dimensions are 500 m in length by 450 m in height. Boundary conditions were applied as follows: the left, right, and bottom boundaries were fixed (zero-displacement), while the top boundary up to the surface was free. Grid discretization was designed considering coal seam extraction conditions and actual geological features. A schematic of the numerical model is shown in Figure 3. The physical and mechanical parameters of the overburden used in the numerical model are listed in Table 1.

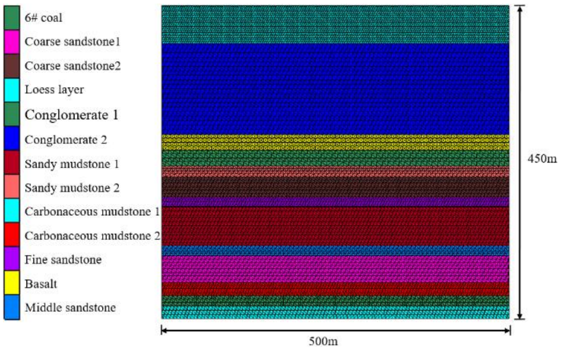


Figure 3. Numerical simulation model diagram

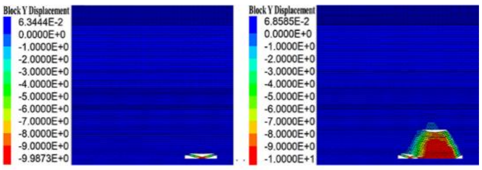
Table 1. Mechanical Parameters of Model Overburden Strata

Lithology	Thickness(m)	Cumulative Thickness (m)	Elastic Modulus E(GPa)	Poisson's Ratio μ	Cohesive Strength C(MPa)	Friction AngleTensile Strength φ(°)	Tensile Strength(MPa)
Loess	55	450	0.0285	7.21	0.0284	15.1	0.29
Conglomerate	130	395	1.7	0.21	1.61	31.5	4.78
Basalt	23	265	85	0.33	3.75	38.5	95
Conglomerate	22.4	242	3.4	0.21	1.61	31.5	4.78
Sandy Mudstone	15.8	219.6	10.2	0.25	2.18	31.5	5.42
Coarse Sandstone	28.8	203.8	16.2	0.41	1.95	36.8	18.64
Fine Sandstone	14	175	16.1	0.16	1.89	37.3	24.01
Sandy Mudstone	56.5	161	10.2	0.25	2.18	31.5	5.42
Medium Sandstone	14	104.5	15.41	0.27	1.8	37.1	14.19
Coarse Sandstone	38.2	90.5	16.2	0.41	1.95	36.8	18.64
Carbonaceous Mudstone	19.3	52.3	8.8	0.28	2.11	28.5	4.78

3.2. Displacement Distribution under Different Coal Seam Thicknesses

3.2.1. Displacement Characteristics for a Coal Seam Thickness of 10 m

The displacement distribution and overburden movement above the goaf during mining of a 10 m-thick coal seam are illustrated in Figure 4.



(a) 100m (b) 200m

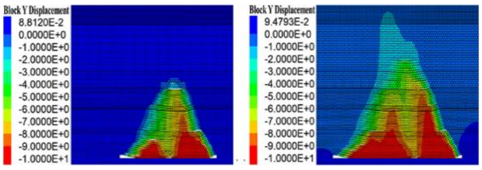


Figure 4. Displacement distribution of the overburden for a 10 m-thick coal seam

When the working face advances 100 m, initial caving occurs, and significant roof subsidence is observed, while the basalt primary key stratum remains intact. At 200 m excavation, the initial caving is complete, and the lower strata have fractured and stabilized; the basalt key stratum still remains unbroken, with a maximum roof subsidence of 10 m. At 300 m, fractures in the lower overburden continue to develop upward but do not penetrate the basalt key stratum; the maximum subsidence remains 10 m. At 400 m, the fracture network reaches the base of the basalt stratum, with the maximum roof subsidence still at 10 m.

3.2.2. Displacement Characteristics for a Coal Seam Thickness of 15 m

The displacement distribution for a 15 m-thick coal seam is shown in Figure 5.

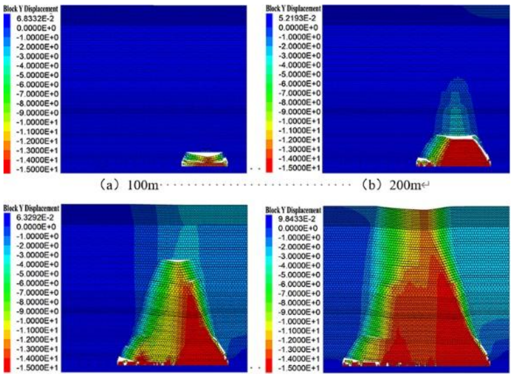


Figure 5. Displacement distribution of the overburden for a 15 m-thick coal seam

At 100 m excavation, initial caving is triggered, resulting in significant roof subsidence, with a maximum displacement of -15 m. By 200 m, the caving zone expands significantly, and roof subsidence increases and gradually propagates into the overlying strata. At 300 m, the basalt primary key stratum fractures and forms a hinged "masonry beam" structure. Following the collapse of the overlying conglomerate layer, a "vault-like" arch structure is formed above the key stratum. At 400 m, the vault-like structure of the conglomerate completely fails, losing its load-bearing capacity. Overburden collapses as fractures propagate through the thick unconsolidated layer, causing particle migration from the unconsolidated layer into the original arch void, which results in surface sinkhole formation.

3.2.3. Displacement Characteristics for a Coal Seam Thickness of 20 m

The displacement distribution for a 20 m-thick coal seam is presented in Figure 6.

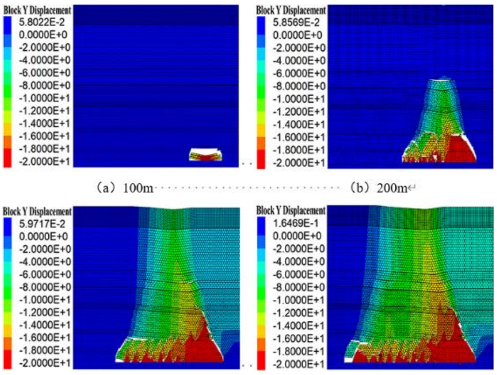


Figure 6. Displacement distribution of the overburden for a 20 m-thick coal seam

At 100 m excavation, the immediate roof collapses concurrently with mining, producing a maximum subsidence of 20 m. By 200 m, the collapse zone further expands, and separation begins beneath the basalt primary key stratum. At 300 m, the basalt key stratum fractures, and the overlying conglomerate forms a vault-like structure that progressively destabilizes. Collapse of the vault structure induces synchronous failure of the overlying sandstone-conglomerate layers, which fill the underlying separation zone and simultaneously cause subsidence of the unconsolidated layer. At 400 m, the fractured basalt forms a hinged masonry-beam structure with the rear basalt blocks, eliminating void space below. Coordinated movement of the overlying strata extends to the surface, producing stepped subsidence, and no further funnel-shaped sinkhole development is observed.

4. SINKHOLE DISASTER CONTROL TECHNIQUES

4.1. Separation-Layer Grouting

Separation-layer grouting is a core technique for controlling mining-induced overburden deformation. Its principle involves filling voids created by roof-layer separation during mining with precisely proportioned grouting material delivered through dedicated drill holes from the surface. High-pressure pumping ensures effective filling and support of the overlying strata, maintaining the integrity of the basalt key stratum, preventing fracture and failure, reducing overburden movement transmission to the surface, and effectively controlling surface subsidence. This enables precise and efficient control of mining-induced overburden failure.

4.2. High-Level Key Stratum Presplitting

High-level key stratum presplitting is an innovative method for controlling hard roof strata, especially under high-strength and large-space mining conditions. Based on hydraulic fracturing theory, high-pressure fluid is injected directionally into the target key stratum to create an artificial fracture network, thereby precisely regulating its mechanical behavior. For hard strata such as basalt, which exhibit high elastic modulus, brittleness, and low permeability, conventional fracturing techniques are insufficient. Controlled injection ensures that fracture pressures exceed the maximum stress on natural planes, promoting tensile and shear failure of pre-existing cracks, and forming a network of interconnected artificial fractures. This technique effectively reduces the overall mechanical strength of the key stratum, transforming originally intact layers into fractured bodies, modifying fracture patterns and energy release, and supporting safe hard roof control. When combined with separation-layer grouting, the overall effectiveness of overburden control is significantly enhanced.

5. CONCLUSION

(1) During extra-thick coal seam mining, the overburden forms a cooperative beam-arch structure. Once the basalt primary key stratum fractures, the overlying unconsolidated layer loses support, leading to potential surface sinkholes.

(2) As coal seam thickness increases, key stratum failure occurs earlier, and surface deformation evolves from continuous subsidence to stepped collapse and sinkhole formation.

(3) The combined application of high-level key stratum presplitting and separation-layer grouting effectively mitigates concentrated overburden failure and reduces the risk of surface sinkhole disasters.

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