Research Development and Critical Problems Existing in Strata Movement and Its Control

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Abstract: Under the guidance of green mining and scientific mining ideas, strata movement and its control have achieved a series of research developments in China. Based on the summary of research achievements related to strata movement characteristics, the influences on mining activity and surface environment, and the utilizing and controlling methods, critical problems that need to be solved are identified for a study on strata movement and its control. Mining activities will cause the redistribution of mining stress. The overlying strata incurs deformation, breaking, and movement under this mining stress. During this period, energy accumulation and release will occur in the roof strata, and the initiation and expansion of overburden fractures will occur. This demonstrates the impact of mining activities on underground safety and the ground environment. Thus, strata movement characteristics in longwall faces should be emphasized in the future. At present, the rock movement is still in the stage of qualitative description. Monitoring the movement of overlying strata in the stope and making predictions according to the monitoring results play a great role in ensuring the safety of mining production. Furthermore, system stiffness theory and intelligent control techniques for overburden strata should be developed.

Keywords: longwall mining; strata movement; mining pressure; mining safety; mining environment; surface subsidence; strata control

1. Introduction

As the predominant energy source in China, coal production has been stable at nearly 4 billion t/a for many years, with longwall mining accounting for up to 80% of this production [1]. Longwall mining is regarded as the most important underground coal mining method in the world’s mining industry due to its advantages of being a simple system, having a high yield, and having a high recovery rate [2]. The inclined length of the longwall working face is hundreds of meters, and the advancing distance is thousands of meters. The mining of the working face will form a large-scale goaf in the rear, which will inevitably cause strong disturbance to the overlying strata of the goaf. The equilibrium state of the strata is broken, and the phenomenon of deformation and failure occurs, which is called strata movement. Strata movement has become a major concern in the mining sector as it has caused a series of negative impacts on mining operations and the mining environment.

Coal strata are sedimentary rocks, generally characterized by soft and hard, thin and thick intervals, resulting in obvious intermittent and unpredictable rock movement at the longwall mining site. Coupled with the non-visibility of the strata interior, early rock movement is considered a black box problem [3].

In order to facilitate the rock control study, the soft rock seam, which is directly above the coal seam and can emerge with mining under the repeated support of the support, is
considered the immediate roof. The immediate roof is broken to form irregular blocks, and the blocks fall to form a highly expansive accumulation that has a filling effect on the extraction space. Above the immediate roof is the main roof, which has a higher strength and thickness. When the main roof cannot be broken in time behind the working face, overhanging above the goaf area, with an increase in overhanging length, the main roof incurs a periodic fracture and forms a large-scale block, and the block movement squeezes the lower mining space, causing roof subsidence, coal wall spalling, hydraulic support work resistance and other mining pressure behaviors. If the main roof belongs to the thick hard strata, it can even cause the roof to weigh over to a great extent and cause other dynamic disasters. After the main roof is broken, the upper rock strata lose the lower support, and broken behaviors continue to develop in the higher rock strata, forming a saddle-shaped mining fissure field [4–6]. Mining fractures then develop in the water-bearing strata, leading to groundwater loss, if the water pressure is high and the mining fractures are fully developed, through the water-bearing strata and working face as a result of the water inrush accident [7].

In addition, the stress redistribution and crack propagation caused by mining provide a force and channel for gas desorption and seepage in coal seams [8]. However, the accumulation of mining stress will also pose a threat to the safety of coal production, causing, for example, rock bursts, coal and gas outbursts, and other dynamic disasters [9–11]. The mining fractures will endanger the surface ecology [12,13]. Mining activities extract resources and energy from the stratum to drive human social development, while causing rock movement and changes to the equilibrium of the stratum stress field, displacement field, fracture field, and energy field, resulting in damage to the surrounding rock and the flow of gas and groundwater [14]. If the rock stratum is not properly controlled, the mining area will incur disaster problems such as roof cavity, coal wall spalling, support crushing, water inrush, rock burst, and coal and gas outbursts, and the surface of the mining area will have environmental problems such as subsidence basins and ecological damage [15]. To solve the series of rock control problems in underground coal mining, it is necessary to apply the black box principle of rock movement and sort out the whole time–space activity process of roof strata. Academician Qian Minggao proposed the strata mechanics of underground coal mining in the early 21st century to study the mechanical behavior of the overlying strata before and after a fracture. Based on the theory of strata movement and control, the theory of green mining was formed, which aims to make full use of the law of strata movement to improve the effects of mine pressure control, to re-utilize all available resources such as land, water, and gas in coal-bearing areas, to reduce the adverse effects of coal mining on the environment, and to realize the coordinated mining of resources and the environment [16,17]. In 2010, Academician Qian Minggao further illustrated the importance of safety, high efficiency, and high recovery rate in coal mining, and proposed safe, efficient, and high recovery rate mining, which together with green mining formed a scientific mining technology system [18,19]. The concept of green mining and scientific mining has pointed out a direction for the development of coal mining science and led China to make significant theoretical and technological progress in underground coal mining in terms of strata movement and control [20].

In summary, the study of rock strata control theory is still in the transition stage from black box to ash box. Improving the visual monitoring means of rock strata movement can help to present the research of rock strata movement as a white box. The concept of transparent geology is the basis for solving the problem of rock movement [21,22]. The differentiated management of stability based on the visualization of rock movement is an effective way to control rock strata.

2. Development History of Strata Movement and Control

The understanding and research for strata movement and control has gone through a long process, including the awareness stage, preliminary research stage, theory
formation stage, rapid development stage, and application innovation stage, as shown in Figure 1.

**Figure 1.** Development history of rock strata movement theory.

The understanding of strata movement can be traced back to the 15th and 18th centuries, when the problem of damage to water resources by underground mining was discovered, but the mechanism of damage and movement of overlying strata by mining was not yet clear. In the 19th century, Gonot, Jicinsky, and other engineers studied the prediction of surface damage after mining from a geometric point of view. Since the 20th century, a number of mining accidents have occurred in underground mines. This has led to the study of rock movement problems being raised to a theoretical level. Stoke proposed the cantilever beam hypothesis in 1916 and Hack and Gillitzer proposed the pressure arch hypothesis in 1928, which became the earliest hypothesis of mine overburden structure and mine pressure. With the application and development of longwall mining technology all over the world, together with the improvement of overburden movement observation technology and support technology, the Soviet scientists Кузнецов and La Paz of Belgium put forward the hypothesis of a “pre-formed fracture beam model” and “voussoir beam model”. After that, strata movement and control technology began to develop rapidly in China, and the “voussoir beam theory”, the “transferring rock beam theory”, the “key stratum theory”, etc., were born [23–25]. In the 21st century, with the rapid development of industrialization, the performance of mining equipment has been improved and the intensity of mining has been enhanced. As coal resources with simple geological conditions are gradually mined out, the coal seams in complex geological conditions are beginning to advance, so the traditional mine pressure theory was innovated for special conditions such as deep-buried seams, extra-thick coal seams, thin bedrock, steeply inclined coal seams, and hard roofs [26–28].

In the initial stage of underground coal and rock mining, rock movement is only treated as a geological phenomenon. With the progress of technology and the increase in work efficiency, people have gained a certain technical understanding of rock movement. Not only have they begun to pursue the efficiency of mining, but underground construction engineers have also begun to focus on the scientific issues related to rock movement. The surface deformation caused by rock movement was measured by a mechanical device. Later, with the progress of measurement technology, digital measurement technology was applied to the mining industry, which made the rock movement gradually progress in the visualization [29].

3. **Movement Law of the Overlying Strata in the Stope**

3.1. **Longitudinal Partition Characteristics**

Strata movement is the root cause of all underground coal mining problems. Ideally, if the pattern and intensity of strata movement is controlled, the problems of the disaster-type instability of surrounding rock, the uncontrolled flow of gas and groundwater, and the irreversible damage to the surface environment will be solved. Strata movement is a three-dimensional spatial problem, and the strata movement pattern should be analyzed.
in both vertical and horizontal dimensions. After coal seam mining, all rock seams from the immediate roof to the surface are affected by different degrees of mining movement. According to the fracture shape and movement characteristics of the strata, they are divided into the caving zone, fracture zone, and bending subsidence belt from bottom to top, as shown in Figure 2.

![Figure 2. Three-dimensional illustration of strata movement.](image)

### 3.1.1. Caving Zone

The strata closest to the coal seam are the most affected by mining, and their fractures are the most developed. After fracturing, they lose continuity completely and fall into the gob as blocks of different sizes, and this part of the rock strata is the caving zone. The fracture movement characteristics of the caving zone have a dominant effect on the mining pressure behavior, and therefore the main focus of strata control studies is concentrated on this area. The lower strata in the caving zone is the immediate roof, and during longwall mining the immediate roof is completely broken in the controlled area, which is all supported by the hydraulic support and falls into the gob after losing support. The immediate roof is broken into irregular blocks and plays an important role in filling the mined area. The compaction reloading characteristics of the accumulated body have a significant effect on high strata movement, section coal pillars stability, and mining pressure distribution. In addition, the internal void structure of the accumulation provides abundant flow channels for gas and water; therefore, the compaction, mechanical behavior and internal structural evolution characteristics of fractured rocks have received considerable attention [30,31]. The 3D scanning method was used to realize a 3D reconstruction of irregular blocks and to conduct mechanical tests. It was found that the compaction mechanical behavior of the accumulated body was controlled by the block translation, rotation, and secondary breaking process, and the block contact changed from point-line mode to surface contact, with the phenomenon of an uneven distribution of force chains. Furthermore the pile stiffness and bearing capacity increased exponentially, and the internal porosity decreased negatively and exponentially, as shown in Figure 3. The study of the compression and deformation characteristics of fractured rock provides theoretical support for the management of gas and water damage in mining areas and the utilization of abandoned mines [32,33].
3.1.2. Fracture Zone

The fracture zone, also called the structural zone, where the lower strata of the region are the main roof, is broken to form more ordered blocks (Figure 2). Academician Qian Minggao established the voussoir beam structural mechanical model by analyzing the block structure morphology and movement mode, considering the broken rock block of the main roof’s rotation and extrusion to form the voussoir beam equilibrium structure with a beam-like appearance and arch-like substance [3,16,23]. The voussoir beam structure has a load-bearing capacity that cuts off the load transfer path of the subsequent strata above the main roof, and the hydraulic support of the mining area only bears the deformation pressure generated by the movement of the structure. Academician Song Zhenqi considered that the overhanging main roof maintains a pseudoplastic mechanical state and maintains a force-transfer relationship in the direction of advance, called a transferring rock beam, with one end supported by the coal wall and one end supported by the gangue in the gob area [24]. The transferring rock beam theory considers that the support has two working conditions of given deformation and given load, and the applied roof pressure depends on the controlled rock beam position. The proposed theories of the voussoir and transferring rock beams elevate the rock control study from a qualitative to a quantitative level of analysis and lays the foundation for the determination of support resistance, the structural form of which is shown in Figure 4.

Figure 3. Compaction characteristics and utilization of the gob.

Figure 4. Structure of the main roof: (a) voussoir beam theory [23]; (b) transferring rock beam theory [24].

On the basis of summarizing the characteristics of strata movement, Academician Qian Minggao put forward the key strata theory, which states that there are several thick hard strata in the overlying strata which play a controlling role in the overall or local strata movement, the former being called the main key strata and the latter being called the subkey strata. The main roof is essentially the subkey strata closest to the coal seam, which controls the fracture and movement of the upper part of the seam. The key strata theory is proposed to realize a synergistic analysis of mine pressure, strata movement, and surface subsidence [34]. According to the relationship between the immediate roof thickness and the mining height, it is found that the lower key strata can form two structures of the
cantilever and voussoir beam, which together with the voussoir beam structure of the higher key strata affect the strength of the mine pressure behavior. The structural mechanics models of the lower cantilever beam, upper voussoir beam, and the upper-lower double voussoir beam are proposed. The instability of the lower structure has no effect on the upper structure, while the instability of the upper structure will cause linkage instability in the lower structure, which explains the large and small periodic pressure phenomenon that exists in the large space between thick coal seams [35]. For the dynamic pressure problem faced by the large mining space, the fold catastrophe model of cantilever beam dynamic fractures and the power trace model of voussoir beams are constructed. Aiming to resolve the problem of the strong mining pressure behavior in the top coal caving mining of extra-thick coal seams in the Datong mine, Yu Bin proposed a far-field overburden structure mechanics model according to the spatial distance between the roof structure and the mining space [36]. Yongping Wu proposed the concept of large inclination coal seams and proposed the method of roof–stope–floor (R-S-F) dynamics analysis, which realized the multi-component synergistic control of the mining structure system [37]. Huang Qingxiang introduced the voussoir beam theory into shallow stope strata control and proposed the structural mechanics modeling of short voussoir beams and step rock beams according to the characteristics of mining pressure behavior in shallow stopes [38]. Based on the complete development of the beam structure theory, Jia Xirong introduced the thin plate structure theory into the field of strata movement research, explaining the reason for the arch-shaped distribution of support resistance along the face length direction and providing a means to analyze the relationship between the mining pressure characteristics and the spatial dimensions of the mining space [39]. In order to solve the problem of the unsuitability of a thin plate theory in analyzing the deformation fracture characteristics of a thick hard roof, Yang Shengli uses a medium thick plate theory to analyze the distribution characteristics of tensile and shear stresses inside the thick hard roof, and gives the transition conditions of the thick hard roof fracture mode from tensile-type to shear-type to realize control over the dangers of roof cutting and the collapse of hydraulic supports in different regions and grades [27]. For thick alluvial layers and thin bedrock stopes, the high voussoir beam is transformed into an alluvial soil-arching structure. The asymmetric and symmetric instability of soil arch structures leads to rock failure in the tensile and shear interval failure modes, and the low cantilever beam-high balance arch and low voussoir beam-high balance arch structural models are constructed, and an alluvial load boundary determination method is proposed. With the promotion of top-coal caving mining and large-height mining technology, the area of highly disturbed rock strata increases, the area of the caving zone expands, several key strata enter the large area influenced by the mining pressure, and the intensity of the incoming pressure becomes strong. The main roof and even the key strata above it enter the caving zone at this time.

In the fracture zone area of the deep mine, the development of fractures in the rock formation decreases with the depth of burial. The horizontal fractures are fully developed in the fracture zone due to the strata delamination phenomenon, and the longitudinal fractures are generated in the tensile stress development area, but the extension is not sufficient to penetrate the full thickness of strata, so the fracture zone still has some continuity, but the non-penetrating fractures provide abundant flow channels for gas and groundwater. Achieving an effective control of strata movement in the fracture zone is particularly critical for gas and water damage management. According to the key strata theory, the separation fracture occurs mainly between the key strata and the lower strata. As the mining area increases, the gangue in the center of the mining area is fully compacted to support the rock strata in the fracture zone, and the fracture in the center is gradually compacted. Accordingly, Academician Qian Minggao discovered the O ring distribution characteristics of the overlying separation fracture, which provided guidance for the arrangement of unloading gas extraction boreholes and formed the idea of coal and coal bed gas co-mining based on strata movement [40]. Xu Jialin analyzed the influence of the location of the key strata on the development height of the fracture zone and
concluded that fracture of the key strata would lead to the height of the fracture zone developing abruptly, which should be determined according to the “Regulations on coal pillar retention and coal compression mining of buildings, water bodies, railways and major shafts” combined with the location of key strata. The cumulative effect of mining overburden unloading and swelling was found, and the influence of mining height, mining depth, and lithology on the amount of swelling was analyzed, and the phenomenon was considered to have an effect on the overburden breakout height, the amount of deviation under the key strata, and the surface subsidence coefficient. Miao Xiexing classifies the key strata of the fracture zone into single-type and composite-type according to the development characteristics of the mining fracture and considers that the rotary closure and dense filling of the mining fracture can achieve the closure of the aquifer and stop the uncontrollable flow of groundwater. Academician Yuan Liang discovered that the annular fracture body in the high overburden of the mined coal seam is the key to achieving efficient gas extraction from low-permeability coal seams and proposed a method to determine the geometric parameters of the high annular fracture body [41].

Based on the theory of strata movement and O-ring theory, the distribution characteristics of the gas flow field are analyzed, and the theoretical system of gas extraction by pressure relief mining is proposed. Academician Wu Qiang reported that the mining-induced fractures are connected to the roof aquifer, and the stronger water richness of the aquifer within the fracture zone is a sufficient condition for the roof water inrush, and the synergistic analysis of the mining fracture field and the groundwater flow field is realized by geological modeling combined with mining simulation [42]. Li Shugang found that the distribution characteristics of the elliptical paraboloid zone of the gas flow channel, formed by the penetration of a longitudinal fracture and the delamination fracture of rock formation; established a mathematical model of the dynamic evolution of the elliptical paraboloid zone; and built a comprehensive flow model of gas unloading and seepage in the expansion of the longitudinal fracture and the uplift of the layers [43]. Lai Xingping divided the process of overburden fracture development into five stages: slow germination → gradual stepwise increase → sudden and rapid increase → small periodic increase → stable development. Furthermore, he proposed a nonlinear prediction method for fracture zone height [44]. Qi Qingxin divided the overburden fracturing field into the low-angle delamination fracturing zone, the medium-angle fracturing zone above the gob, the high-angle fracturing zone, and the medium- and high-angle transition zone, and the analysis results of the fracture characteristics of the four zones indicate that the medium- and high-angle transition zone is the core area of gas extraction [45].

3.1.3. Bending Subsidence Belt

Above the fracture zone is the bending subsidence belt; there is no mining fracture development inside the rock strata in this area, and it remains completely continuous. As shown in Figure 2, coal seam mining causes strata movement that is visualized at the surface as the appearance of subsidence basins and surface fractures. Since the strength of the quaternary alluvium near the surface is extremely low and nearly loose, the probability integration method, vector model method, and time function method for surface subsidence prediction are proposed. The prediction method based on mathematical and statistical principles is widely used in the continuous type of surface subsidence prediction, but the mathematical method ignores the influence of rock movement on the surface subsidence process and treats all rock strata above the coal seam as simple, which differs greatly from the reality. Academician Qian Minggao classified surface subsidence into three categories: gentle wave type, cracking type, and step type. He did this based on the characteristics of overlying key strata movement and differences in topsoil layer conditions, and the mathematical method is only applicable to the first category of continuous-type subsidence prediction [16]. In the process of monitoring the coupling movement of key strata and the topsoil layer, Xu Jialin found that under the condition of a thin topsoil layer and large mining height, the uneven subsidence of key strata cannot be absorbed by the topsoil
layer, and the fracture and instability of the key strata trigger the sudden change in surface subsidence [46]. Wang Jinzhuang considered the mining area and whether the bedrock was fractured in full thickness to classify the surface movement of the thick loose layer into bended type, fractured type, and sufficient type, and found that the bedrock fracture led to a sudden change in the amount of surface subsidence [47]. Zuo Jianping proposed the “analogous hyperbola model” which models movements inside and outside the strata by fitting the boundary morphology to describe the static characteristics of overburden movement and surface subsidence, respectively.

3.2. **Horizontal Partition Characteristics**

3.2.1. Toward Zoning Characteristics

The long wall mining space is large, and overburden strata movement in the horizontal direction also presents zoning characteristics. According to the time for which the sequence of mining was influenced, it is divided into the original rock stress area, the advance abutment pressure concentration area, and the strong mining delaminated area above the stope and gob gangue recompaction area in the direction of advance (Figure 2). Academician Qian Minggao used the limit equilibrium theory to derive the forward support pressure distribution curve, constructed the overburden mechanics model with the help of elastic foundation beams and the key strata theory, and found that the peak abutment pressure decreases with the increase in coal seam and immediate roof thickness, and the peak position shows a trend away from the coal wall. Song Zhenqi proposed the concept of an internal stress field and an external stress field of abutment pressure according to the movement process of a transferring rock beam and coal wall damage; the external stress field is formed by high strata load transfer, and the internal stress field is caused by the rotational deformation of a transferring rock beam. Xie Guangxiang discovered a macro stress shell existing in the overlying strata [48]. The stress shell cuts off the stress transfer routes inside and outside the shell; the voussoir beam is located in the decompression zone under the shell, bearing only the subordinate strata load of the shell; and the two ends of the shell are borne by the unmined coal body, forming advancing abutment pressure. Jiang Fuxing proposed the concept of dynamic and static abutment pressure fields [49]. The dynamic abutment pressure formation and evolution are the result of strata movement in the rupture zone of the mining roof, the static abutment pressure is the result of the load transfer of the strata above the rupture zone, and the mining stress transfer model is constructed based on the state of the key strata. The movement of the strata causes a concentration of advanced mining stress while also causing the mining stress to deviate from its original direction, called mining stress rotation. The rotation trajectory of the mining stress is controlled by the workface advance direction, and eventually rotates to a vertical plane parallel to the direction of the advance, tilted toward the mining void area in that direction and tending to tilt toward the roadway space, as shown in Figure 5 [41, 50-53].

![Figure 5. Stress rotation characteristics of different propulsion degrees.](image-url)
3.2.2. Tendency Partition Characteristics

The length direction of the working face is divided into the fully compacted area, the non-fully compacted area, and the overhanging roof coal pillar support area according to the overburden structure and the compaction characteristics of the falling gangue in the mining area, as shown in Figure 6a. The phenomenon of strata movement zoning in the direction of face length is also the reason for the appearance of non-homogeneous characteristics of mining pressure in the extra-long working face. For the deep fracture development in stopes, the mining pressure behavior shows an obvious asymmetry in the direction of face length; for example, the mining stress in the first mining face of a mining area should be symmetrically distributed, but the microseismic monitoring structure shows that the strata movement on the tail gate side is significantly more active than that of the main gate side, as shown in Figure 6b. The asymmetry of the strata movement is caused by the asymmetry of the mining stress rotation trajectory, as shown in Figure 6c. The mining stress rotation trajectories (II) at the tail gate side of the stope fall within the stress orientation-sensitive areas associated with two fracture sets, and the trajectory (III) at the main gate side is covered by the stress orientation-sensitive area of one fracture set; therefore, the strata activity at the tail gate side is more frequent and the number of microseismic events is higher but carries lower energy values.

![Figure 6](image_url)

**Figure 6.** The phenomenon of strata movement zoning: (a) compaction characteristics of gob area; (b) asymmetric distribution of microseismic activity; (c) the mining stress rotation trajectory.

4. Influence of Strata Movement on Mining Safety and Environment

The visual manifestation of strata movement in the mining space is the roof subsidence and caving. If the immediate roof is severely broken, the roof is prone to inter-support fall and end-face fall, as shown in Figure 7a,b. Improper control of the altitude of the supports in the process of moving the supports leads to large gap between the supports, causing the phenomenon of inter-support fall that can easily injure workers. The end face fall can fall suddenly and can easily bury the coal mining equipment, causing the bracket topping rate to decrease or even become unsupportive, reducing the stability of the bracket. In addition, the broken block produced by the immediate roof cannot move with the support canopy, causing the phenomenon of the support becoming stuck and the difficulty of moving support, and the excessive thrust of the shifting jack will lead to the destruction of the local components of the support canopy, which must be repaired by the staff before normal movement resumes, as shown in Figure 7c. The main roof fracture and structural instability above the immediate roof will produce a dynamic load impact phenomenon on the lower immediate roof and supports, and if the supports are improperly selected or the roof plate is widely destabilized, crushing of the supports will occur in the stope, as shown in Figure 7d. A dynamic disaster in the stope seriously threatens the safety of personnel and equipment near the longwall face. Therefore, it is of great safety significance to predict strong mine pressure based on the characteristics of mine pressure if you want to realize the differential management of the surrounding rock in the longwall face.
At present, the prediction method of pressure is usually used by on-site construction technicians to predict the deformation of the roof and coal wall based on their experience. With the improvement of monitoring technology’s function and accuracy, it has become more and more safe to use roof microseismic information to predict strong mine stress.

The transfer of a strata load above the mining area to the unmined area causes the phenomenon of advanced mining stress concentration. Mining fractures develop in the coal seam, driven by mining stress; coal wall spalling occurs after the coal wall is exposed; and large pieces of spalled coal block the miner’s machine path, causing downtime of mining equipment and reducing the startup rate, as shown in Figure 8a. The high bearing pressure triggers strain energy accumulation in the large buried coal rock body; the dynamic load impact caused by the roof breaking and destabilization causes the coal rock to be subjected to dynamic and static loads simultaneously; and the strain energy stored in the coal rock body is suddenly released under the double drive of high static load and dynamic load disturbance, causing dynamic disasters such as rock bursts and coal and gas outbursts, as shown in Figure 8b. If the roof belongs to the hard strata, a wide range of overhanging roof will be formed above the mining area, which cannot be broken off and fall over time. When the overhanging area reaches the limit span, the whole hard roof is cut down, causing the weighting over great extent disaster, the gas in the mining area at the same time gushes into the mining space, causing the gas to exceed its space limit or even a hurricane-type phenomenon. When there is a pressurized water-bearing layer in the roof strata, if the development height of the caving zone reaches the pressurized water-bearing layer, the water quickly gushes to the mining space along the mining fracture, triggering a sudden water accident, as shown in Figure 8c [54]. For the thin bedrock stope, the bedrock shows full-thickness fracture mode, the ability of key strata to control this kind of overburden is reduced, and the full-thickness fracture in the bedrock cuts down along the coal wall to cause a roof-cutting accident, generating large-aperture mining fractures above the working face, and the loose layer above the bedrock is carried along the mining fractures by the water to gush into the working face, causing a water-sand inrush accident, as shown in Figure 8d [55].

Rock movements change the surface morphology, forming subsidence basins and surface fractures that disrupt the continuity of the surface, as shown in Figure 9a. If there are houses, railroads, and other structures located in the area covered by the subsidence
basin, house cracking and road damage will occur, as shown in Figure 9b [56]. If the water table in the mining area is higher than the amount of surface subsidence, water will form in the area covered by the subsidence basin and affect the normal use of the surface, as shown in Figure 9c. If the water table in the mining area is lower than the surface subsidence, especially for the more ecologically fragile western mining area, mining causes groundwater loss and root damage to surface vegetation, resulting in the drying of large areas of vegetation and damage to surface ecology, as shown in Figure 9d [57]. In addition, underground mining work produces a large number of coal gangue, including the formation of gangue mountains on the surface. Gangue mountains occupy land resources; gangue contains a large number of toxic chemicals, and a reaction occurs under the action of water or direct sunlight, polluting the air of the mine. There is a need to invest huge human and material resources in gangue mountain management, before its reclamation and reuse, as shown in Figure 9e,f.

Figure 9. The influence of strata movement on the environment: (a) surface fracture; (b) road fracture; (c) subsidence water area; (d) vegetation withered; (e) before the treatment of gangue mountain; (f) after the treatment of gangue mountain.

5. Relationship between Mining Support and Surrounding Rock

The coal miner strips the exposed coal of the working face from the parent body and transports it away by the scraper conveyor, and the roof plate thus loses the support of the coal body. At this time, the hydraulic support temporarily supports the roof plate to ensure the safety of personnel and equipment in the working face area. The coal seam is excavated to form a space that can only be temporarily supported by hydraulic supports. Since the stiffness of the supports is less than the coal body, the roof plate generates force on the hydraulic supports in the process of bending and deformation. The research on the monitoring of the mine pressure behavior in the mining area focuses mainly on the monitoring of the mine stress and roof deformation [58–60].

For in situ measurements of mining stress, the instruments used are borehole stress gauges and hollow shell strain gauges [61–64]. The former is used to monitor the magnitude of the vertical dynamic stresses in front of the working face, while the latter can monitor the magnitude and direction of mining stress as the face advances. The deformation monitoring of the roof has always been a black box problem. At present, the resistance and subsidence of the hydraulic support can be used to reflect the degree of roof deformation in the direction of the length of the working face [65]. The use of microseismic monitoring technology can provide an indirect monitoring of the roof damage [66,67]. After the
overlying strata is broken, it diffuses in the form of stress waves in a spherical form. The sensors arranged around the working face infer the source position and initial energy according to the time difference and energy information of the received stress wave signal. In these monitoring methods, testing for mining stress can only be based on the stress information of a certain point in the coal body. At the same time, the long-distance drilling construction is slow, and the drilling trajectory is difficult to control. The high degree of fracture development in the coal body and the poor stability of the borehole will lead to data limitations of the borehole stress meter and hollow inclusion strain gauge, which make it difficult to reflect the stress distribution of the whole mining area. The microseismic monitoring method consists of an indirect measurement, and the positioning accuracy is difficult to be verified due to the heterogeneity of rock mass. Therefore, in the actual measurement, the deformation characteristics of the surrounding rock can be directly reflected by analyzing the deformation and force situation of the support.

6. Application and Control Methods of Strata Movement

6.1. Application Methods of Strata Movement

Strata movement is a double-edged sword. While it poses a threat to mine safety and the mining environment, underground coal mining can take advantage of strata movement to improve mining efficiency. The coal seam mining conditions are different, and the main roof may form structures such as a voussoir beam, transferring rock beam, cantilever beam, etc. According to the differences in the main roof structure movement position and the control target, the structural balance method, dynamic load method, binary criterion method, and three-factor coupling method for bracket resistance determination are proposed to guide the hydraulic bracket selection. The bending and sinking characteristics of the roof strata and the changing characteristics of the support resistance are obtained by actual measurement, so that the relationship between the support resistance and the rock movement is obtained. The improved coupling performance between the support and the surrounding rock provides guidance for the optimization of the support structure,
reduces the degree of force concentration in the local components of the support, and improves service life [78]. Based on the phenomenon of stress concentration in advance mining caused by strata movement, the method of top coal caving mining from thick coal seams was proposed to make full use of mining stress to promote top coal crushing, to use small equipment to achieve thick coal seam mining, and to reduce investment [79]. Based on the principle of key strata on rock movement control, the concept of water protection mining is proposed, and, to realize the application of key layer theory in water protection mining, the principle of water barrier key strata is elaborated in four aspects: water barrier key strata discrimination, structural stability discrimination, seepage stability discrimination, and seepage mutation channel control. Considering the delaminated space appearing between the key strata and the underlying rock strata and the mining unloading phenomenon, Academician Yuan Liang proposed the ideas of gas extraction and protective layer mining to realize the co-mining of coal and gas and the effective deconstruction of prominent coal seams. The fallen gangue accumulation in the mining area contains a large number of voids with considerable water storage capacity, while the internal pores of broken rocks have the ability to purify water, according to which academician Gu Dazhao proposed the idea of underground water reservoirs to achieve water and energy storage and an effective use of abandoned mining areas [80]. Academician He Manchao made full use of the lateral roof structure and proposed the 110 engineering method of self-forming a roadway without coal pillars with the help of deep hole blasting and roof cutting, combined with a constant resistance large deformation cable support, which effectively reduces the loss of coal pillar resources in the panel. Based on the dynamic surface subsidence process caused by strata movement, Academician Wang Shuangming proposed a geologically guaranteed theory of loss-reducing green mining to achieve effective damage reduction during mining and rapid recovery after mining by clarifying the coupling mechanism between the strata structure and the ecological development of the surface.

6.2. Methods of Controlling Strata Movement

Underground coal mining allows for the disturbance of the strata, but the degree of disturbance should be controlled within a reasonable range to avoid underground disasters and surface ecological problems. The function of the hydraulic support is to protect the quarry area. The coupling relationship between the support and the surrounding rock is studied to control the amount of roof subsidence within the acceptable level for safe mining and to prevent the occurrence of roof cavity accidents. For hard roofs, in order to avoid dynamic disasters such as weighting over great extent, rock bursts, coal, and gas outbursts caused by roof breakage, presplitting blasting technology, hydrofracturing technology, supercritical CO$_2$ fracturing technology, and other means are used to generate artificially damaged fractures in thick hard roofs to promote roof breakage and fall. In order to reduce the amount of surface subsidence and enhance the water isolation capacity of the key strata, overburden separation grouting filling technology was proposed to achieve a subsidence reduction with the synergistic support of the key strata and the filling body. For coal mining areas with high surface subsidence control requirements, an integrated mining–dressing–backfilling synergistic mining technology is proposed, which realizes underground intelligent sorting of coal and gangue, modular storage transportation, underground production of gangue-based filling material, and compacted filling. The integrated mining–dressing–backfilling synergistic mining technology achieves the gangue without ascending the well, avoiding the damage of the gangue mountain to the surface environment and the huge investment required for the greening work. According to the characteristics of strata movement under different mining boundary conditions, by reasonably controlling the mining sequence and mining parameters, the tensile and compressive deformations during surface subsidence can be complemented to ensure that the surface achieves continuous subsidence in a moderate mode to achieve a source loss reduction.
7. Key issues Discussion on Strata Movement

7.1. Full Process Description

The application of a beam and plate theory to strata movement clarifies the roof structure morphology and strata movement development process, reveals the intrinsic relationship between strata movement, mine pressure, and surface subsidence in the mining area, and proposes a series of rock movement control methods. However, the above studies only realize a qualitative analysis of the strata movement process, and do not realize a quantitative description of the strata movement trajectory. In the future, more complex mining boundary conditions and more physical and mechanical parameters of rock formations should be included in the study of strata movement with the help of theories on elastic-plastic mechanics and fracture mechanics, so as to realize an accurate judgment of the deformation fracture characteristics of rock formations. Then, a dynamic analysis of the fracture block movement process should be carried out with the theory of rock block mechanics, and equations of non-regular block translation and rotation trajectories should be constructed. The construction of strata movement trajectory equations can explain the causes of the large discontinuous deformation of roof strata from the perspective of the system dynamics, provide quantitative guidance for the selection of supports in the stope, and lay the foundation for proposing a method for predicting surface subsidence based on strata movement.

7.2. Unified Field Theory

The research on mining pressure and surface subsidence has been fragmented for a long time, and it is difficult to establish the mechanical connection from the perspective of total overburden strata movement. The law of strata movement in the far field is unclear, and the mechanisms of dynamic disasters, non-solid associated resource flows, and the surface subsidence associated with it is unknown, which has become the main problem in thick coal seam mining, as shown in Figure 10. In the future, the mining stress distribution in thick coal seams and its driving mechanism of overburden fracture extension should be studied, followed by an exploration of the mining fracture distribution and a determination of the influence of the fracture field on the strata movement pattern. Then, the development characteristics of the overburden displacement field driven by strata movement should be analyzed, and a surface subsidence prediction method should be proposed by considering the process of complete overburden movement. Finally, the mechanism of overburden multiphysical field coupling caused by strata movement should be investigated, the conditions of dynamic disaster occurrence and the flow law of non-solid associated resources should be explored, and the methods of dynamic disaster prevention and control and the protection of associated resources should be proposed to realize the safe and scientific mining of thick coal seams.

Figure 10. Unified field theory diagram.
7.3. Complex and Difficult-to-Mine Coal Seam

7.3.1. Steeply Inclined Stope

After mining the steeply inclined and near-erect coal seams, the boundary conditions of the overhanging roof are obviously different from those of the traditional stope, and the component of the strata load perpendicular to the coal seam face is much smaller than that parallel to the coal seam face, so the overhanging area of the steeply inclined coal seam roof increases and is less likely to collapse. For such conditions, the applicability of a traditional plate and beam theory in their stability analysis needs to be analyzed, and the control of the key strata on the strata movement is weakened. Especially in the process of cooperative mining of multiple coal seams, the roof between the coal seams is not easily broken, forming an almost upright towering rock column, and the deformation of the rock column forms an extrusion on the coal seams, so the mining stress concentration phenomenon in the mining process of steeply inclined coal seams occurs in the unmined coal seams in the lower section. The large difference between the mining pressure and surface subsidence patterns in the steeply inclined coal seam and the traditional mining area indicates that the laws of strata movement need to be further investigated in order to formulate a theory of strata control applicable to the steeply inclined mining conditions and to provide guidance for alleviating the mining pressure and surface subsidence loss in the mining area.

7.3.2. Deep Longwall Panel with Thin Bedrock

Similar to the shallowly buried thin bedrock stope, the deep longwall panel with thin bedrock stope typically has only one key strata, which has a reduced ability to control rock movement. A full-thickness fracture of bedrock is likely to cause strong mine pressure accidents on the roof and water–sand inrush disasters. However, the existence of giant thick alluvium leads to different strata movement patterns in deep buried thin bedrock stopes than in shallow buried stopes, and the applicability of the short voussoir beam and step rock beam theories in deep buried thin bedrock stopes needs to be further investigated. Strata movement in deeply buried thin bedrock stopes is not controlled by key strata but is dominated by a periodic destabilization of the giant thick alluvial arch structure. In order to improve the stratification control effect of deeply buried thin bedrock stopes, it is necessary to further investigate the controlling role of giant thick alluvium in stratification movement and clarify the mechanism of alluvial load transfer.

7.4. Stiffness Theory for the Surrounding Rock Support System in Large Space Mining Panels

The surrounding rock structure system in the mining space consists of the coal wall, roof, support, floor, and waste rock of gob. Excessive local deformation of any system component will affect the stability of the structural system, so the relationship between the stiffness of the system component and the control effect of the surrounding rock in the stope was considered, and a model of the stiffness of the surrounding rock system was constructed. The traditional strata control theory for support selection focuses on whether the rated resistance of the support satisfies the requirements to resist the pressure of the roof. The results of the system stiffness model analysis show that the support stiffness has an important influence on the stability of the coal wall, the greater the support stiffness, the stronger the ability to support the roof, and the smaller the roof load transferred to the coal wall. However, the selection of the support stiffness should take into account the actual conditions of the roof and floor to suit the local conditions. If the integrity of the roof and floor is high, the high-stiffness support can give its full effect to the protection of the coal face; if the roof and floor are broken, the high stiffness support can hardly play an effective role, and the roof load will continue to be transferred to the coal face, causing the cost of stope preparation to increase. In summary, it is necessary to establish a theory of the stiffness of the surrounding rock support system, coordinate the relationship between the stiffness of the system components, complete the optimal support stiffness selection,
quantify the design and manufacture of hydraulic supports with target stiffness and strength, and improve the effect of surrounding rock control on the stope.

7.5. Intelligent Control Methods and Technologies for Strata Movement

Underground coal mining is rapidly moving toward intelligence, and intelligent strata control is the most critical step in achieving intelligent mining. The acquisition, transmission, analysis, and feedback of rock movement information provide the basic data for the realization of intelligent control. An intelligent mining model with multi-parameter fusion should be constructed first, and a real-time dynamic and multi-source heterogeneous awareness of strata movement information should be realized by advanced physical exploration means such as microseismic systems, ground penetrating radars and transient electromagnetic methods. The realization of the rapid transmission of massive data is achieved with the help of the Industrial Internet of Things. The realization of the rapid analysis and screening of strata movement data achieved with the help of deep learning, big data, cloud computing, and other technologies to master the strata movement state and reconstruct the strata movement process with the help of virtual reality technology. The aim is to be able to quickly search for strata movement methods, provide feedback to mining equipment based on strata movement position and control objectives, and make adjustments to equipment working conditions and settings. With the help of advanced physical information systems, it will be possible to realize the rapid detection of strata movement information and mining environments and the adaptive control of mining equipment. Finally, intelligent mining parameters and processes are proposed to fully achieve the intelligent control of rock formations, and the technical path is shown in Figure 11. The remote start to using coal mining equipment and unmanned stopes was realized in the Tashan Mine, Yangquan Coal Mine, and Huangling No. 1 Coal Mine in China. The equipment posture and roof state are all digitally presented and uploaded to the dispatching center in real time. The monitoring data are fed back to the mining parameter control system to realize the adaptive mode and adjust the operating state to its best.

Figure 11. The technical path for intelligent strata control.
8. Conclusions

In this study, based on the summary of research achievements related to strata movement characteristics, the influences on mining activity and the surface environment, and the utilizing and controlling methods, the critical problems that needed to be solved for the study on strata movement and its control are identified, and the following main conclusions are reached.

(1) Longwall mining causes discontinuous and large strata deformation. Mining pressure and surface subsidence are the visual forms of near-field and far-field strata movement. The relationships between mine pressure, strata movement, and surface subsidence in the stope are established based on the key stratum theory. The strata movement is divided longitudinally into the caving zone, the fracture zone, and the bending subsidence belt according to the different degrees of mining disturbance, and it is divided into the original rock stress area, the advance abutment pressure concentration area, the strong mining delamination area, and the re-compaction area according to the duration of the disturbance to the sequence of mining. The tendency of strata movement is divided into the fully compacted zone, the non-fully compacted zone, and the coal pillar support zone according to the different support conditions.

(2) Considering the broken block occlusion pattern in the caving zone, structural models, such as the cantilever beam, voussoir beam, and transferring beam, are formed to guide the ground control. The structural balance method, dynamic load method, binary criterion method, and three-factor coupling method are proposed for the support selection. The concern in the fractured zone is the mining fracture, especially the delamination fracture development characteristics, which forms the O-ring theory. A gas extraction technology, key stratum water protection mining technology, and overburden separation grouting filling technology are proposed. The variation principle is utilized to demonstrate the subsidence surface in key stratum at the fracture zone, which provides a guidance for the key stratum water isolation capacity evaluation and delamination space determination. The coupling subsidence characteristics of the surface and the main key stratum are focused on the bending subsidence belt, and a hyperbolic-like model is proposed.

(3) Strata movement leads to the mining stress concentration and mining stress rotation phenomena. Mining stress concentration drives the static destruction of roof caving, rib spalling, and water-sand inrush. The overlapped drive of stress concentration and roof dynamic load on the dynamic failure of the surrounding rock results in the sudden release of strain energy, causing weighting over great extent, rock bursts, coal and gas outbursts, and other dynamic disasters. The asymmetric distribution characteristics of the mining stress rotation trajectory cause the phenomenon of partitioning of the surrounding rock stability, which explains the causes of the asymmetric distribution of microseismic activity in the stope. Aiming at various disasters caused by strata movement, pre-cracking blasting, hydraulic fracturing, supercritical CO2 fracturing, and filling mining are proposed for the roof strata to avoid the emergence of uncontrollable strata movement patterns. The enhancement method of surrounding rock stability based on the goal of optimizing the mining stress rotation trajectory is established.

(4) The proposed theory of beams and plates raises the analysis of strata position to a quantitative level, but the process of strata movement still remains at a qualitative level, and a cross-examination of mechanical theory and dynamic analysis methods is needed to realize a quantitative analysis of the whole process of strata movement. The visualization of strata movement is the basis for its quantitative analysis. Accurate rock movement measurements will result in a better correlation between rock movement and mine pressure behavior. It is important to determine the relationship between the supports and the surrounding rock and implement differentiated
management for areas with high damage risk to the surrounding rock at the working face, which has an important effect on improving the stability of the surrounding rock. The key strata theory realizes a synergetic analysis of mine pressure, strata movement, and surface subsidence in the stope, but does not reveal the driving principle of strata movement on the process of mine pressure generation and surface subsidence in the stope. A unified field theory of strata movement should be established to realize the common perception of the positional field, displacement field, stress field, energy field, and fracture field of strata movement. The applicability of the traditional beam and plate theory in the strata movement of complex and difficult coal seams has yet to be investigated, and it should be clarified as soon as possible in order to realize the scientific mining of complex and difficult coal seams.

In addition, the development of rock strata intelligent control methods and technologies, and the construction of a theory of the stiffness of the surrounding rock support system in the stope are also worthy of attention.

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