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Review

Research Findings on the Application of the Arch Structure Model in Coal Mining, a Review

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Abstract: Studying the movement law and failure mechanism of overburden is important to underground safety production, aquifer protection, surface subsidence and ecological protection. A commonly used model, the arch structure model, for studying overburden movement is systematically reviewed in this paper. First, the arch structure in the mining field is divided into an unconsolidated layer arch, beam arch (hinged arch), and overburden arch according to arching medium. On this basis, the research progress and existing problems of these three arch structure models are discussed according to the research means, including theoretical modeling, numerical simulation, similar simulation, and field measurements. The application of the arch structure model focuses on the prediction and prevention of mining pressure and surface subsidence, and there are relatively few means to actively regulate overburden arch. Thus, three control methods of the arch structure in underground coal mining are proposed: the preset arch structure method before coal mining, process control arch methods during coal mining, and end reinforcement control arch methods after coal mining. Finally, the main research focus on the arch structure model in the future is discussed.

Keywords: underground coal mining; arch structure model; unconsolidated layer arch; beam arch; overburden arch; arch structure control

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1. Introduction

The structure model of overlying strata in mining fields can be used to describe strata movement and predict mine disasters [1–3]; it is the foundation of safe mining in underground coal mines. The overburden structure theories and hypotheses proposed for mine pressure and rock strata control mainly include: key strata theory [4–6], transfer rock beam hypothesis [7], masonry beam theory (articulated rock block hypothesis) [8], hypothesis of pre-cracked beam [9], cantilever beam hypothesis [10], and the stress arch hypothesis [11]. These theories and hypotheses have been widely used and developed in coal mining. For example, the key strata theory has been applied in working face periodic pressure and support resistance prediction [4], the development of water flowing fracture zones [6], filling, mining, and surface subsidence [12,13], rockburst prevention and control [14], pressure relief mining and gas extraction [15], water inrush prediction from the floor [16], and grouting in separated layers [17]. The transfer rock beam hypothesis has led to important achievements in the innovation of mining methods and mining technologies, as well as the control practice of major accidents and disasters, such as the design of mining methods without coal pillars, the calculation of support resistance, the prediction of three-zone height, the prevention and control of rockburst, coal, and gas outburst, etc. [7,18]. Masonry beam theory, preformed fracture beam hypothesis and cantilever beam hypothesis all reveal the fracture and migration characteristics of overburden rock above the working face with the beam model, and provide the prediction model of mining pressure of the working face under specific geological conditions and mining parameters. The arch structure model, evolved on the basis of the beam model, can not only analyze the near-field mine pressure law, but also explain the characteristics of overburden and surface migration in the far field, which is widely used in the analysis of overburden fracture migration in coal mining. For example, in the process of coal seam mining, due to the existence of the stress arch, the adjacent coal seams will generate a stress increase zone and stress relief zone. If the adjacent coal seam is in the stress relief zone, the gas seepage capacity of the coal seam will be greatly improved, which is conducive to the gas drainage of the coal seam [19,20]. This paper classifies the overburden of the arch shell, discusses the related research findings and the application of the overburden arch shell structure, and, on this basis, puts forward the possible research focus in the future.

2. Formation of the Arch Structure Model Hypothesis

In the process of arch formation analysis and its application development, it can be divided into two aspects. On the one hand, it is applied to the stress distribution of the surrounding rock of coal mine roadways, and provides guidance for roadway support design. On the other hand, the overburden stress arch studied in this paper mainly focuses on the stress change and fracture migration structure of overburden in the mining field. This section mainly discusses the formation and development of the overburden stress arch model hypothesis.

The phenomenon of surrounding rock arch formation was first summarized by Ritter [21], demonstrating that the stress in the tunnel soil layer does not increase with the increase in buried depth. Subsequently, Terzaghi, Fayol, Engesser, Handy et al. [22,23] referred to such arched bearing structures in the soil (unconsolidated body) as the arch effect. Therefore, in the beginning, the arch effect is mainly used in granular materials (such as tunnel excavation in soil), and is rarely used to explain the bearing structure of rock strata. However, it provides a reference for the analysis of stable structures of rock strata in coal mining. Hack and Gillitzer [24] were the first to apply arch structure to the analysis of mining pressure in coal mines. Based on the "stress arch" hypothesis proposed by Apehc [25], they used the stress arch hypothesis to explain the evolution of abutment pressure during the advancing process of the coal face, as shown in Figure 1. This hypothesis can reliably explain the pressure relief area of surrounding rock, but the specific characteristics of the arch, migration, and fracture of overburden rock, and the support resistance of the mining field, are not further involved.

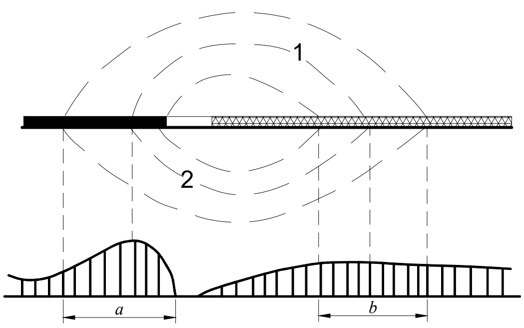

Figure 1. Stress arch in mining face. a–Front arch foot; b–rear arch foot; 1–roof arch structure; 2–floor arch structure.

Subsequently, Ime [26] proposed the hypothesis of stress arch and its influence on confining stress more systematically, and believed that the existence of the stress arch in the roof formed the pressure relief area in the arch, and the stress rise area in the arch rock strata. Dinsdale [27] pointed out that after the coal seam mining, the surrounding rock would form an oval pressure ring (similar to Figure 1), and presented the correlation between the pressure ring and the mining width of the working face and the surface subsidence. This was the first time researchers analyzed the mining subsidence problem using the arch effect.

After that, scholars gradually began to pay attention to the location of the overburden arch, arch formation conditions, and other characteristics of the arch itself. Stemple [28] put forward that the condition of arch formation is that the buried depth must reach the critical depth. For example, the requirement of fracture arch formation at the present stage is that the buried depth of the working face should be greater than the height of the fracture zone. Denkhaus [29] provided the evolution model of the stress arch, believing that the stress arch moves forward with periodic roof caving, and the arch foot is the crushed rock compacted in goafs. Subsequently, with the development of computing ability, numerical analysis methods based on the finite element stress vector model and the discrete element caving model were gradually applied to the study of arch characteristics [30]. Chekan [31] and Luo et al. [32]. conducted in-depth research on the height to span ratio and shape characteristics of arches. However, with the withdrawal from coal mining in some developed countries, the development of an overlying arch hypothesis has gradually stagnated, especially after entering the 21st century; the development of the arch hypothesis and its related applications is, therefore, mainly important in China.

Zhao [33] introduced the natural balanced arch in analyzing the stress distribution of roadways. Miao [34] further analyzed the correlation between the natural balance arch and the stability of roadway surrounding rock, and presented the corresponding relationship between the pressure measurement coefficient and surrounding rock arch shape. It can be seen that the stress arch was mainly applied to the stress distribution of roadway surrounding rock at first, and the research on the stress arch of overlying rock in mining fields further promoted the application of the arch hypothesis in coal mining in China. Cao [35] put forward the composite stress arch model of the roof. Zou [11] presented a new interpretation of the stress arch according to the actual situation of coal mining in China. Kang [36] explained the process of roof breaking into the arch with the help of discrete element numerical simulation, and verified the role of arch structure in maintaining the stability of overburden. In the 21st century, with the rapid development of the Chinese coal mining industry, the theoretical model is continuously in-depth, numerical simulation technology is widely used, and the laboratory and field monitoring methods are constantly updated. There are more and more studies on the arch stress structure model. For example, in the characteristics of the arch structure model, it mainly involves the arch forming and breaking conditions, arch trace, arch stress distribution, arch thickness, arch-bearing capacity, two-dimensional arch, and three-dimensional shell, etc. In the aspect of coal mining parameters, mainly including mining height, working face length, advance speed, backfill mining, caving mining, strip mining, room and pillar mining, etc. In terms of the geological conditions of coal mines, it mainly involves the dip angle of the coal seam, the lithology (strength) of the roof and floor, the overburden medium (unconsolidated layer), and the depth of the coal seam. In terms of the application of the arch model, it involves the prediction of surface subsidence, the calculation of pressure coming from the working face, and the working resistance of the support, the design of hydraulic fracturing in the roof, the pressure relief gas extraction, and the prevention of water inrush from the floor, etc. Therefore, abundant achievements have been made in the research of the arch structure model, which provides a basis for the research and analysis of overburden migration, mining pressure behavior, gas extraction, and surface subsidence in coal mining.

3. Construction of Arch Structure Model

3.1. Model of Unconsolidated Layer Arch Model

The geological conditions of the thick unconsolidated layer are widely distributed in some mining areas in East China and North China, such as Huainan, North Anhui, Huaibei, Yanzhou, Xinwen, Kailuan, and other mining areas. The maximum thickness of the unconsolidated layer in 48 coal mines is 752 m, the minimum is 100 m, and the average is 319 m. It is found, from this measurement, that in the mining of the shallow coal seam, the load of the thick unconsolidated layer (mainly viscous unconsolidated layer) does not act on the main roof at once, and there is an arch-bearing structure, as shown in Figure 2.

Therefore, the load of the unconsolidated layer on bedrock cannot be simply equal to the weight of the unconsolidated layer, and it is necessary to study the evolution process of the unconsolidated layer arch model. At present, studies on the unconsolidated layer arch mainly focus on the geological conditions of the shallow buried thick unconsolidated layer, and analyze the influence of the unconsolidated layer arch on surface subsidence, fracture development, and the unconsolidated layer on bedrock load [37,38].

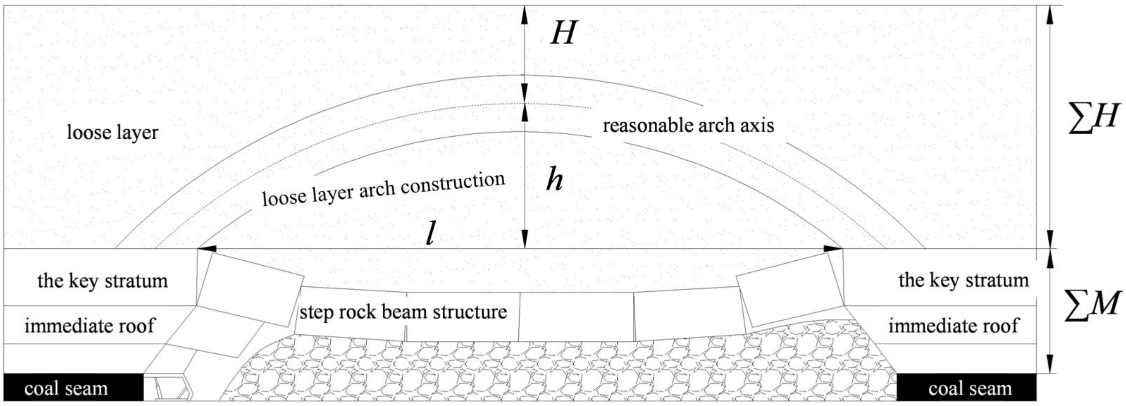

Figure 2. Unconsolidated layer arch structure in mining overburden. l–Span of arch structure; h–height of arch structure; H–burial depth of arch crown; $\sum H$–thickness of unconsolidated layer; $\sum M$–thickness of bedrock.

3.2. Arch Structure Model of Overlying Rock

(1) Linear arch (beam arch)

Beam theory is widely used in the analysis of overburden fracture and migration in coal mining. It is believed that once the flexural and tensile strength of the beam is exceeded, the yield failure will expand along the beam, and the effective thickness of the beam will be reduced due to transverse fracturing, which is an important conclusion of classical beam theory. However, the span of the arch structure formed during underground mining, surface subsidence, and transverse beam fracture is much longer than that predicted by classical beam theory. This behavior can be attributed to the formation of a linear arch in the beam, referred to in this paper as a beam arch (or hinged arch). On the basis of specific geometric structure, the principal stress traces in a thick rock layer show an arch distribution. As shown in Figure 3, the resistance acting on both ends of the beam leads to the formation of stress arches in the beam [39]. In a given range of the thickness to span ratio, the beam arch can bear a higher load than that predicted by traditional beam theory. At present, the beam arch model is mainly applied to analyze the strong mining pressure phenomenon caused by thick and hard roof structures.

(2) Overburden arch (stress arch, fracture arch)

At present, the overburden arch (three-dimensional "shell") model is mainly divided into the fracture arch and stress arch models [40–43]. The fracture arch is generally considered to be the top boundary of the overburden where the fracture occurs, so it usually has no thickness; the stress arch refers to the arch stress zone formed by the deflection of the overburden principal stress in the mining field, with a certain thickness [44], as shown in Figure 3. The double-arch model of overburden in mining fields is the mechanical manifestation of rock mass self-bearing characteristics and the compressive stress arch effect. Considering the traditional subzones of overburden in coal mining (caving zone, fracturing zone, and bending zone), the fracture arch can be considered as the range of the caving zone and fracturing zone, or as the boundary of the area where the caving zone and fracturing zone are located.

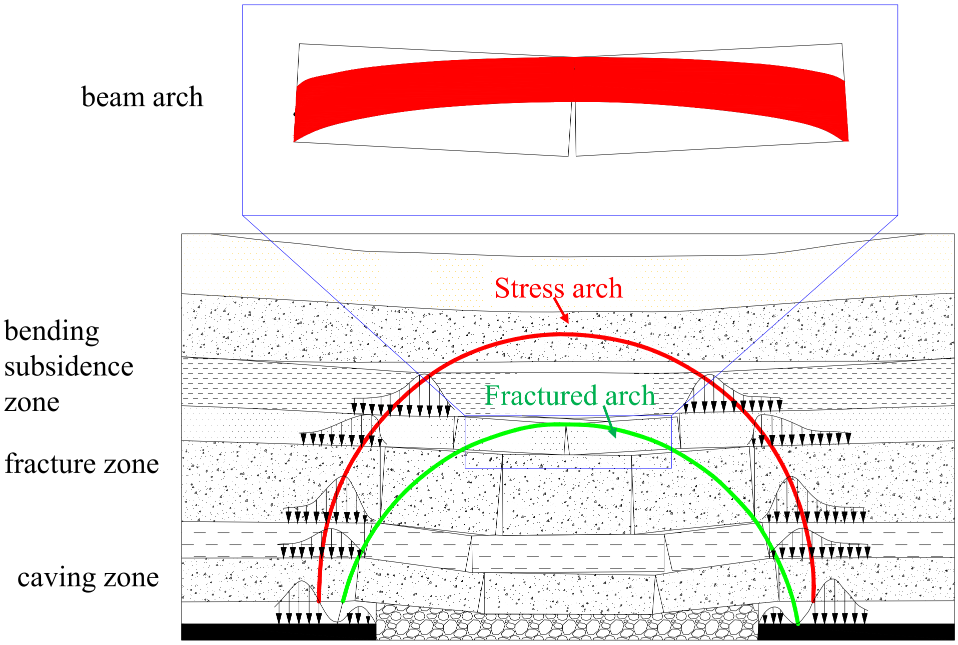

Figure 3. Overburden arch structure based on beam arch structure.

The stress arch is generally located in the upper part of the fracture arch, and is the bearing structure of the whole overburden. In fact, the stress arch is mainly caused by the stress relief of the fracture arch, which transfers the original bearing stress to the upper rock layer, and then forms the stress increasing area. Therefore, the stress arch has a certain thickness, which is the area enclosed by the stress in the overlying rock greater than the stress in the original rock. In addition, the stress arch can also be considered as the "far-field arch", which controls the migration of the whole overburden and surface [43]. As shown in Figure 4, compared with the inclined fracture arch and stress arch of the working face (Figure 3), the near-field arch belongs to the evolution structure of an arch in the direction of advance. The near-field arch is mainly formed by periodic fracture of the main roof, and moves forward with the advance of the working face, accompanied by arch formation and arch breaking. The far-field arch is generally composed of the key stratum. With the advance of the working face, the span of the far-field arch in the direction of advance is constantly expanded, but the arch height is basically unchanged, and gradually evolves into a flat-top arch.

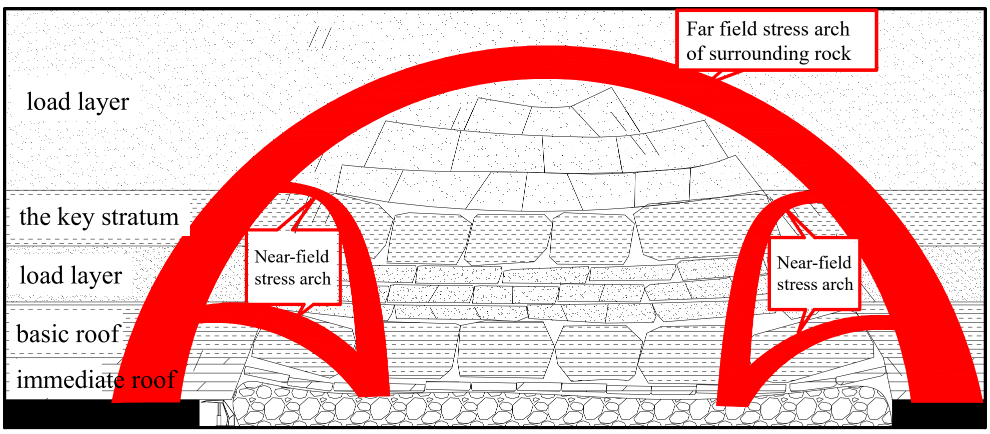

Figure 4. Evolution characteristics of far- and near-field stress arch in overburden.

4. Research Findings and Its Application of Unconsolidated Layer Arch Model

4.1. Research Findings of Unconsolidated Layer Arch

(1) Theoretical model

On the basis of arch theory, the unconsolidated layer arch structure model was established. The unconsolidated layer is regarded as a homogeneous medium in the model. The formation conditions of the unconsolidated layer arch structure were determined by calculating the equation of shape characteristic, the equation of sagittal ratio, and the equation of thickness, and the mechanism of arch formation and its influencing factors were revealed. The expression of the stress arch based on Figure 5 is shown in Equation (1) [37,38]:

$$\begin{cases} x^2 - L_{arch}x + \lambda y^2 + 1/(4H_{arch})(L_{arch}{}^2 - 4\lambda H_{arch}{}^2)y = 0 \\ \frac{H_{arch}}{L_{arch}} \geq \frac{\sqrt{(C+\gamma h_0 \tan\varphi)^2 + \lambda\gamma^2 h_0^2 - \gamma h_0 \tan\varphi - C}}{2\lambda\gamma h_0} \\ \delta_{arch} = \frac{\gamma h_0 L_{arch} \tan(45^\circ + \varphi/2)\cos\varphi}{\gamma(h_0 + iL_{arch})\tan(45^\circ+\varphi/2) + 2C} \end{cases} \tag{1}$$

where x and y are the arch trace coordinates of the unconsolidated layer; $I = H_{arch}/L_{arch}$; λ is the lateral pressure coefficient; φ (°) and C (MPa) are friction angle and cohesion in the unconsolidated layer, respectively; and γ is the bulk density of bedrock, kN/m. After determining the arch forming condition and calculating the arch baseline equation, the load of the unconsolidated layer arch acting on the bedrock can be further determined.

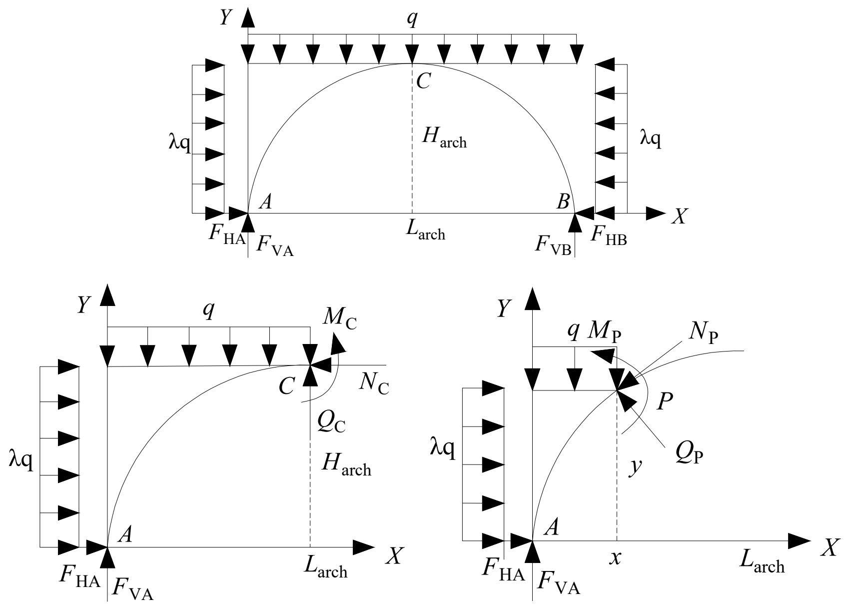

Figure 5. Mechanical structure diagram of unconsolidated layer arch. H_{arch}–Arch height; L_{arch}–arch span; λ–lateral pressure coefficient; q–load; F–support force of arch foot; M–bending moment; N–axial force; Q–shear force.

(2) Numerical and similarity simulation

Based on the construction of the theoretical model, the morphological characteristics of the unconsolidated layer arch structure and the dynamic evolution process of arch structure in the unconsolidated layer were described by PFC, UDEC discrete element numerical simulation software, and similar material simulation [37,45]. PFC is a particle-specific discrete element simulation software, and the particle morphology can effectively simulate the characteristics of the unconsolidated layer. Therefore, PFC^{2D} numerical simulation software can be used to analyze the spatial evolution law of the unconsolidated layer arch. In the process of working face mining, a stress chain in the form of an arch is assembled in the unconsolidated layer, and the shape of the unconsolidated layer arch is represented by the inner and outer envelope of the force chain zone, as shown in Figure 6a. The UDEC numerical simulation generally uses Voronoi blocks to simulate the unconsolidated layer, and describes the arch structure of the unconsolidated layer through the envelope of the principal stress concentration area. As the width of the working face gradually increases, the envelope of principal stress concentration gradually rises, and the degree of principal stress concentration gradually increases, but the height to span ratio of the unconsolidated layer arch structure scarcely changes, as shown in Figure 6b. Through two numerical simulation results, it can be seen that the shape and stress distribution of the unconsolidated layer arch can be well presented by numerical simulation. Similar physical simulation is similar to numerical simulation, which can reveal the spatial evolution characteristics of the unconsolidated layer arch structure in the process of working face mining from the shape of arch and the layout of stress meter, and then reveal the load transfer effect based on unconsolidated layer arch structure.

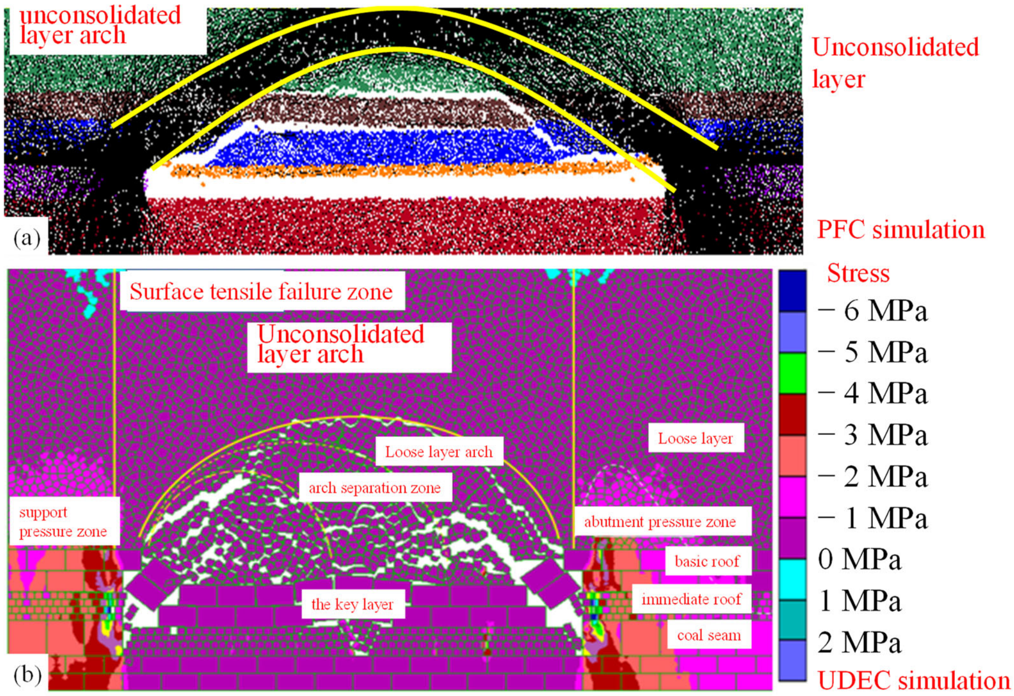

Figure 6. DEM evolution characteristics of arch structure in the unconsolidated layer.

(3) Field measurement verification

At present, the main purpose of studying the unconsolidated layer arch is to better obtain the influence mechanism of the unconsolidated layer arch on load transfer, rock movement, surface subsidence, overburden fracture, and instability, that is, the unconsolidated layer arch can be considered as a part of the overburden arch. Liu et al. [46] studied the movement and deformation law of overlying under the condition of the thick unconsolidated layer by physical simulation, which showed that the edge of the surface movement basin converged slowly, and the boundary angle was small when mining under the thick unconsolidated layer. Thus, the existence of the unconsolidated layer arch could be verified indirectly by field measurement results of surface subsidence. Through field measurement, Li [47] obtained that the surface of the thick unconsolidated layer is sensitive to the influence of mining, the surface movement, and deformation, the recession time is long, and the subsidence velocity and coefficient are large, which can also verify the existence of unconsolidated layer arch. Ju et al. [48] took the surface subsidence caused by coal mining under the thick unconsolidated layer of the Shuozhou mining area as the background, and revealed the surface subsidence mechanism of mining under the thick unconsolidated layer. In conclusion, the field measurement verification of the unconsolidated layer arch is essentially based on surface subsidence characteristics to indirectly verify the existence of unconsolidated layer arch.

4.2. Application of the Unconsolidated Layer Arch

The unconsolidated layer arch structure is mainly used in predicting the height of the water-conducting fracture zone in the thick unconsolidated layer, determining the working resistance of the stope support, and predicting the surface subsidence. Huang et al. [49–51] found the arch effect in the mining of a shallow, buried thick unconsolidated layer coal seam through similar simulation test, and determined the height of the unloaded arch during the initial pressure using the arch structure model, and provided the calculation formula of the stress component and load factor of arch structural failure. Furthermore, the criterion of sand arch fracture and the calculation method of the specific location of surface tensile fracture are provided. Zuo et al. [52,53] constructed an arch structure model of thick unconsolidated overburden and provided the calculation formula of surface subsidence range. Wang et al. [37,38,54,55] determined the calculation formula of working face support resistance based on the arch structure of the unconsolidated layer. Based on the influence of unconsolidated layer arch structure on overburden and surface movement, the characteristics of overburden movement and surface subsidence based on the coupling effect of the unconsolidated layer arch structure and key stratum structure are revealed, and the surface subsidence law of coal mining under the thick unconsolidated layer is obtained. On the basis of mastering the relationship between overburden and the unconsolidated layer, the strip filling mining technology based on controlling the arch structure of the unconsolidated layer and the stability of key blocks is developed, the critical mining width and critical filling rate are determined, and the surface subsidence control under thick unconsolidated layer is realized.

It can be seen from the above examples that the application of the unconsolidated layer arch model is mainly based on the geological conditions of the thick unconsolidated layer, and the model of the unconsolidated layer arch is used to predict the surface subsidence and the mining pressure of the working face.

5. Research Findings on the Application of the Overburden Arch Model

5.1. Research Findings of Overburden Arch Model

(1) Theoretical model

The theoretical model studies on beam and arch were mostly concentrated in mining. Cook et al. [56] applied the theory of beam and arch to the fracture analysis of overlying strata for the first time, trying to explain the rockburst phenomenon of deep gold mines in South Africa. Then, Sterling [57], Brady and Brown [58], Wold and Pala [59], Seedsman [60], Pells and Best [61], Sofianos and Kapenis [62], Diederichs and Kaiser [63], and Nomiko et al. [64] conducted a series of laboratory studies and field verification on this theory, and further developed the beam arch theory. The following assumptions are generally made when the beam arch model is constructed: (a) the beam is subjected to horizontal, symmetric, and uniformly distributed loads; (b) the supporting arch is rigid, and the hardness of the contact point is large enough; (c) Poisson's ratio of rock mass is 0; (d) before the beam is deflected, there is no lateral stress limiting the beam; (e) the loading environment is in a plane strain state. Brady and Brown [58] demonstrated the basic principles and characteristics of beam arch formation: (a) the roof strata forms hinged blocks due to natural penetrating fractures or mining-induced fractures, hence the continuous elastic beam or plate theory cannot be applied; (b) under the action of gravity load, the roof rock block forms the hinged beam arch by the lateral binding force; (c) the beam arch can be elastic in a certain range (that is, the transverse thrust–vertical deflection curve is linearly reversible), and the upper limit is close to the peak transverse load capacity; (d) for a beam arch with low span to thickness ratio, the most likely failure mode is shear failure at the arch support; (e) for a beam with high span to thickness ratio, the span stability is limited by the bendability degree of the beam, and there is no obvious splitting phenomenon in the middle and both ends; (f) for a beam arch with low rock strength or moderate span to thickness ratio, it may be unstable due to the crushing or peeling of the middle or both ends of the beam.

With the introduction of the key stratum theory, the key stratum, as a thick and hard rock, is more consistent with the beam arch theory. The thick and hard strata represented by the key strata are important load-bearing frameworks and force-transmitting structures, and their principal stresses are significantly higher than those of the adjacent strata, which play a dominant role in the macroscopic evolution of the mining stress field. Through mechanical analysis, Lou [39] showed that the force of thick and hard rock strata, represented by the key stratum, during bending deformation was significantly higher than that of neighboring rock strata with small thickness and low stiffness. Zhao et al. [65] quantitatively analyzed the variation characteristics of principal stress in each area of the beam arch in a single key stratum based on the geological conditions of the single key stratum in the Shendong mining area. Thus, the beam arch model is mainly combined with the articulated beam model, focusing on the evolution mechanism of the stress arch in thick and hard strata (key strata) of mining fields, and then studying the instability mechanism of the whole overburden structure.

The research on overburden arch is mainly established by applying the three-hinged arch model from the perspective of structural mechanics, and most of these are based on the compressive arch theory and Terzaghi soil arch effect. It is assumed that a semi-circular, semi-elliptical, and parabolic model can be used to deduce the morphological characteristic equation and identify the instability of the arch model [66]. In the model construction, it is basically similar to the steps of the unconsolidated layer arch, realizing the modeling of arch trace, and applying it to the prediction of mine pressure and mining subsidence. The theoretical model of the overburden stress arch can be summarized as follows:

① Before the construction of the stress arch model, the arch track shape is assumed, such as semi-circle, semi-ellipse, and parabola shape, and then the stress arch model under the assumed track shape is produced, and the stress load analysis under the relevant state is carried out.

② Although the overburden of a coal mine has obvious bedding characteristics, the strengths of the rock strata are also obviously different. The overburden is assumed to be homogeneous in the construction of the stress arch model, which is basically consistent with the modeling of the unconsolidated layer arch. However, the actual rock strata are inhomogeneous layered rock masses, including hard and soft rock strata. In addition to the large difference in the lithology of each layer, there are obvious weak planes between layers. To solve this problem, Lu et al. [67] proposed the recursive method of the fractured arch, that is, the equation of the fractured arch of the lower strata was solved first, and the equation of the upper layer was established on the basis of the solution of the next layer. This actually reverts to the calculation of the fracture arch of a single rock stratum, and extends the beam arch model to the stress arch model.

③ In the process of setting the boundary stress of the overburden arch, uniform load is generally applied above the arch, and the size is proportional to the buried depth, which is consistent with the boundary conditions of the unconsolidated layer arch (Figure 5). Considering the large depth span of the overburden stress arch, the loads on the left and right sides of the arch are developed from the initial uniform load to the trapezoidal load considering the buried depth. The magnitude is the vertical stress multiplied by the lateral pressure coefficient at its location. From the setting of stress boundary, it can be seen that the stress inside the arch is not taken into account in the process of constructing the arch structure model. However, there is rock mass support under both the stress arch and the fracture arch. Therefore, the current theoretical model of the overburden arch is more inclined to caving due to the stress boundary conditions.

④ The construction of the stress arch model is mainly to obtain the trace equation of the arch. The main parameters involved in the arch construction process include coal seam burial depth (H), arch height (h), arch span ($2a_0$), overburden firmness coefficient

f (or overburden cohesion, internal friction angle), lateral pressure coefficient λ, and bulk density γ; the trace equation of arch can be expressed as Equation (2).

$$q_0 x^2 = 2a_0 f q_2 z + \left[\frac{(q_2 - q_1)z^3}{h} + 2q_1 z^2\right]\frac{2q_2 + q_1}{3(q_2 + q_2)} \tag{2}$$

where $q_0 = \gamma(H - h)$; $q_1 = \lambda\gamma(H - h)$; $q_2 = \lambda\gamma H$. The trace equation of "stress arch" can be obtained by replacing x and z in Equation (2) with span and arch height. After the trace equation of the arch is obtained, the bearing state of the arch can be further deduced, and the conditions for forming and breaking the arch can be judged.

⑤ There is no method to determine the arch thickness of overburden stress. The unconsolidated layer arch model proposed by Wang et al. [37] provides the calculation equation of arch thickness, which is mainly determined according to the range of abutment pressure in advance of the arch foot, and assumes that the thickness of the arch and the arch foot is the same. However, this is not applicable to the model of the heterogeneous overburden arch, and the thickness of arch obtained by numerical simulation is not consistent.

(2) Numerical simulation and similarity simulation

Aiming at many defects in the process of theoretical model construction, such as stress boundary setting, rock lithology, and arch trace pre-setting, numerical simulation can be used to study the evolution characteristics of overburden arch in the process of coal seam mining because it is intuitive and close to the field engineering situation. The numerical methods used for the simulation of the overburden arch mainly include a finite element and discrete element. The finite element is mainly FLAC^{3D}, while the discrete element is mainly UDEC and PFC software, consistent with the unconsolidated layer arch. The arch formation characteristics are judged by observing the deflection of principal stress in the process of coal seam mining (Figure 7) [43]. Because the numerical simulation can visually display the magnitude and distribution of stress, the existence of the stress arch can be verified, and the arch thickness can be further obtained. For example, the overburden stress arch forming index k ((maximum principal stress − maximum principal stress of original rock)/maximum principal stress of original rock) is used to partition the overburden, and then the main location of stress arch is determined (Figure 8) [68].

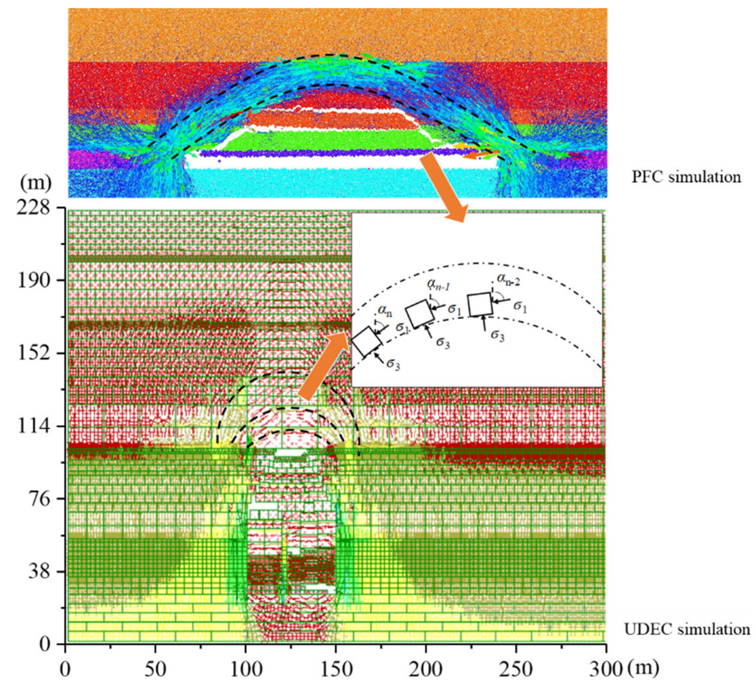

Figure 7. Principal stress deflection into arch mechanism.

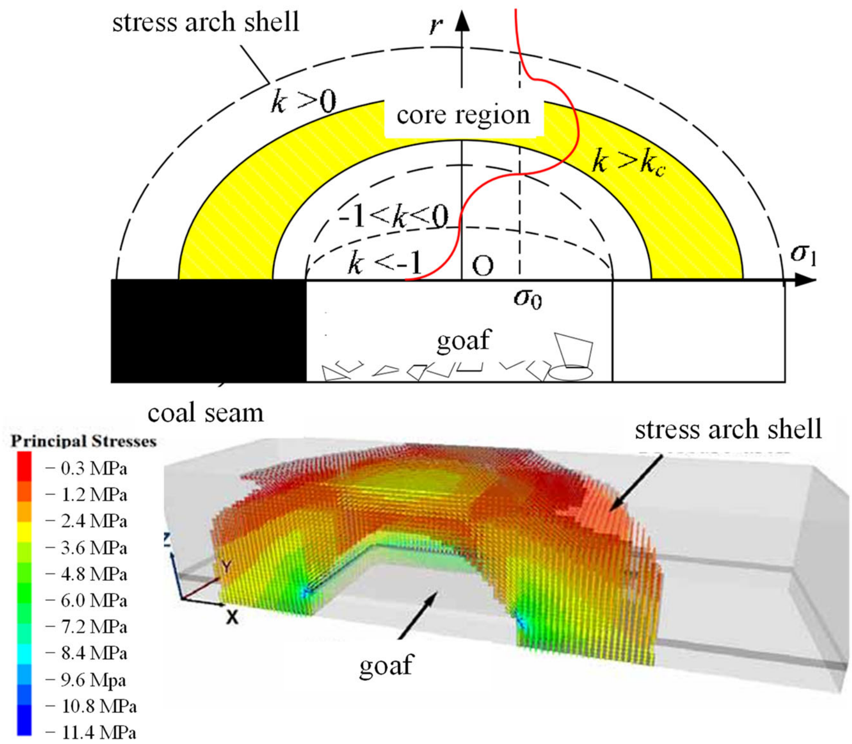

Figure 8. Stress arch zoning and FLAC^{3D} simulation results.

The distribution evolution characteristics of the stress arch and its correlation with mining technology and mining parameters are mainly obtained based on FLAC^{3D}. Xie et al. Researchers [40,41,69–72] have conducted a large number of FLAC^{3D} simulation studies, and some believed that there is a stress arch structure in the mining field, and thus have analyzed the influence of lithology, mining height, and working face length on the development law of the stress arch. Xie et al. [73] used FLAC^{3D} to analyze the distribution and evolution characteristics of the stress arch in the process of backfill mining. Luo et al. [74] used FLAC^{3D} simulation to classify the mining-induced stress concentration arch and pressure relief zone, which is helpful to further analyze the characteristics of gas migration. However, FLAC^{3D} model is generally a continuum model, which cannot simulate rock fracture and caving. In the simulation process, plastic zone is often used to simulate the development form of the arch model, as shown in Figure 9 [75,76]. It can be seen from the figure that the shape of the plastic zone is two-dimensional arch (or three-dimensional shell) in the stage of insufficient mining, and two-dimensional "saddle" (or three-dimensional "basin") when it reaches the state of full mining.

Based on discrete element 2D simulation software such as UDEC and PFC, the evolution of stress arch and fracture arch, and the influence of overburden fracture on arch evolution, are mainly obtained. Xie et al. [77] used PFC numerical simulation software to simulate and analyze the evolution characteristics of force chain in surrounding rock of mining field, and the simulation results are similar to Figure 6a. Through UDEC simulation, Du et al. [29] concluded that the existence of stress arches prevented the upward development of mining-induced fractures, and slowed down the mining pressure in the working face. Zhang et al. [78] used UDEC numerical simulation software to analyze the stress distribution characteristics of the "double-arch bridge" structure in the roof of the goaf, and obtained the stress transfer law. Two-dimensional software can only simulate the shape of the arch of the working face tendency or strike, but cannot realize the description of three-dimensional space. In addition, the particle size or block division of the two-dimensional model directly affects the fracture or caving characteristics of the overlying rock. Taking UDEC as an example, the thickness of the rock block and the division of the vertical fractures all affect the caving shape of the rock layer.

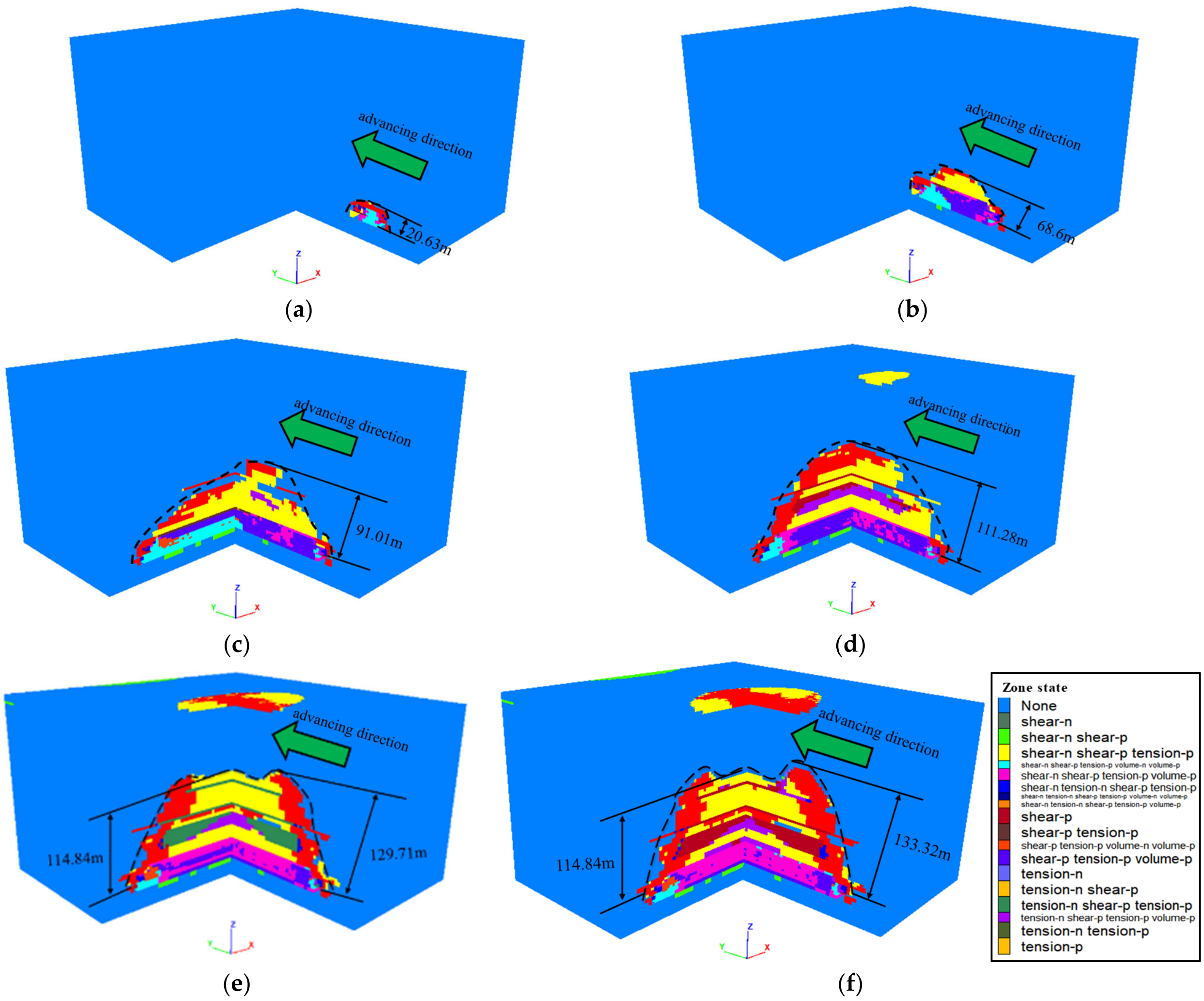

Figure 9. Development process of overburden damage zone. (**a**) advance 50 m; (**b**) advance 150 m; (**c**) advance 200 m; (**d**) advance 250 m; (**e**) advance 280 m; (**f**) advance 300 m.

Thus, numerical simulation can well provide the location, thickness, and evolution characteristics of the arch model. However, the stress arch model simulated by finite elements ignores the influence of rock fracture, while the stress or fracture arch model simulated by discrete elements depends on the division of blocks. In view of the above problems, the finite discrete element method can solve them well [79,80]. However, this method is rarely used to simulate arch structure at present. This method is more used for simulation of rockfalls, particle breakage, coal pillar instability, etc. [81–84]. In addition to numerical simulation, similarity simulation is also the main means to study overburden arch structure. At present, the similarity simulation is mainly two-dimensional, which is similar to the discrete element simulation. However, the similarity simulation mostly focuses on the description of fracture arch morphology and evolution process, which makes it difficult to realize the simulation analysis of stress arch [85–87]. Therefore, generally, similarity simulation and numerical simulation are used to verify each other in the process of arch structure model analysis [88].

(3) Field measurement verification

Although there are many studies on the theoretical analysis, numerical simulation, and similar simulation of overburden arch, and many research results have been achieved, there are few literatures on the field measurement of the existence of overburden arch. On the one hand, the field measurement is difficult, expensive, and has a certain impact on production; on the other hand, there is a lack of targeted monitoring means. Therefore, at present, the method of field measurement and verification of overburden arch is basically the measurement of the height of fracture zone. The default is that at the top boundary of fracture zone development is the location of fracture arch. The method of combining the measurement of flushing fluid loss and drilling television observation is the most widely used field test method [89,90]. This method can accurately measure the height of water-conducting fracture zone, but it needs a lot of time, manpower and money. Transient electromagnetic instrument, three-dimensional seismic and other methods can effectively detect the permeability of mining-induced overburden fractures, and comprehensively analyze the changes of apparent resistivity and aquifer water level to predict the evolution law of water-conducting fracture zones [91]. Sun et al. comprehensively used a variety of technical means to detect the height of the "two zones" of overburden, and believed that the accuracy of borehole color TV and borehole flushing fluid loss was significantly better than that of transient electromagnetic geophysical exploration [92].

5.2. Overburden Arch Structure Model Application

To obtain the position, bearing capacity, fracture, and instability conditions of the overburden arch by means of theoretical analysis, numerical simulation, and similar simulations is mainly to study the law of fracture and migration of overburden in coal mining. On this basis, mining problems such as mine pressure in the working face, height of water-conducting fracture zone, surface subsidence, and surface fracture development can be predicted. Fracture arch is mainly used to predict the height of the water-conducting or gas-conducting fracture zone. The stress arch is mainly used to determine the pressure relief range and predict the overburden fracture migration. Fu et al. [93] provided the calculation method of the working resistance of the support using the stress arch model constructed according to the geological characteristics of deep and weak bonding. According to the characteristics of shallow, buried extremely soft roof, Li et al. [94] explained the phenomena of primary pressure and periodic pressure using the stress arch model. Luo et al. [74] used the stress arch model to divide the stress concentration area and pressure relief area, and further analyzed the migration characteristics of pressure relief gas. Wang et al. [95] proposed the composite stress arch and explained the relationship between overburden migration and surface subsidence. Xu et al. [96] believed that there was no stress arch stage, single-stress arch stage, or double-stress arch stage in shallow, buried high-intensity mining, and predicted the periodic development law of surface fractures. The above research shows that the current research and application of the overburden arch are mainly focused on mastering the evolution characteristics of overburden arch and its influence on the pressure migration of overburden, so as to carry out related passive treatment.

Therefore, how to control the development and evolution characteristics of overburden arch actively, so as to control the overburden fracture migration and mining pressure evolution, is an important content to study the control of overburden arch structure on overburden fracture migration. By studying the control effect of overburden arch on separation, Su et al. [97,98] proposed the grouting technology of overburden separation to ensure the stability of overburden arch and control the surface subsidence. Liu et al. [99,100] proposed arch structure grouting and subsidence control technology for abandoned mined-out areas of coal mine, and proposed corresponding grouting parameters and locations. In addition to maintaining the stability of the arch, under certain geological conditions, the long-term unbroken overburden arch will also cause dynamic hazards. In view of the phenomenon of hard and thick roof being difficult to break and resulting in strong mining pressure, Xia et al. [101], based on the overburden arch model, proposed the technology of roof hydraulic fracturing for arch breaking.

6. Prospects for the Study of the Arch Structure Model

This paper systematically summarizes the research findings of unconsolidated and overburden arch models in coal mining, and divides the arch structure model into three categories according to the region and research object: unconsolidated layer arch, beam arch, and overburden arch. The unconsolidated layer arch is mainly aimed at the geological conditions of the thick unconsolidated layer. Since the geological conditions of the unconsolidated layer are similar to those of the Terzaghi soil arch effect, the soil arch theory can effectively explain the stress distribution characteristics in the unconsolidated layer and the load action of the unconsolidated layer on bedrock. Beam arch is put forward for single-layer thick and hard rock, and combined with the relevant characteristics of articulated beam, the theory of articulated arch is put forward. The formation and breakage of the unconsolidated layer arch are judged. The overburden arch is mainly proposed for the whole overburden structure, and can be divided into stress arch and fracture arch. The fracture arch is generally considered as the top boundary of the fracture zone in coal mining, while the stress arch is considered as the stress increasing area in the overburden. In general, the formation of the beam arch is the key to the formation of the overburden arch. Based on the main research results, the research findings of arch structure model and the future research focus are shown in Table 1.

Table 1. Main research findings of the arch structure model.

Main Aspects	Specific Parameter Characteristics		Research Findings
Arch structure characteristics	Arch forming condition		The arch forming condition of the unconsolidated layer arch is that the thickness of the unconsolidated layer is greater than the sum of the maximum rise height and thickness of the unconsolidated layer arch; The arching condition of the overburden fracture arch is that the overlying bedrock thickness of the working face is greater than the height of the fracture zone in the full mining stage; The arch forming condition of the overburden stress arch is sufficient horizontal stress; The arch forming condition of the beam arch is that a single, thick, hard rock layer can be broken to form an articulated structure
	Arch breaking condition		The instability modes of the arch: compression instability mode, tension instability mode, shear instability mode, and composite instability mode
	Trace shape of arch		Arch trace mainly includes elliptic, semi-circular, parabolic, catenoid, hyperbolic function shape, etc. (3D ellipsoid or spherical). With the continuous advancing of the working face, arch shape evolves dynamically
	Stress distribution of arch		The area where the arch axis is located is the stress increasing area; The outer part of the arch is the stress area of the original rock; The inner part of the arch is the pressure relief area
	Arch thickness		In numerical simulation, it is considered to be the range of stress increasing area, while in theoretical model, it is mainly the arch foot thickness
Mining process parameters	Room and pillar mining method		The evolution characteristics of stress arch in room-and-pillar mining are similar to those in roadway surrounding rock
	Strip mining method		The strip mining stress arch is similar to the roadway stress arch, but the width of the separated coal pillar affects the independence of the adjacent strip stress arch
	Longwall mining method	Fully mechanized top coal caving	The protective effect of stress arch formed by fully mechanized caving mining is greater than that of fully mechanized mining
		Filling mining	Compared with caving mining, the height of the arch structure is greatly reduced, and the shape of the arch is flat
		Mining height	With the increase in mining height, the arch height increases
		Length of working face	The stress concentration degree increases with the increase in working face length, the arch height increases gradually, and the flat rate increases
		Advancing speed	The advancing speed can improve the bearing capacity of the arch
		Width of coal pillar	The coal pillar width affects the superposition of the stress arch of two adjacent longwall working faces, and there is a critical coal pillar width. When the coal pillar width is larger than the critical coal pillar width, the stress arch of the two working faces are independent of each other

Table 1. *Cont.*

Main Aspects	Specific Parameter Characteristics	Research Findings
Geological conditions of rock stratum	Arching medium	The unconsolidated layer arch is formed under the condition of the thick unconsolidated layer. Single-layer thick hard rock formation beam arch; The overburden arch is mainly proposed for the whole overburden structure, and it can be divided into stress arch and fracture arch
	Lithology	The lithology is strengthened, the height of the stress arch is reduced and tilted, the bearing capacity of arch is enhanced, and the risk of dynamic disaster is enhanced
	Dip angle	In the coal seam with high dip angle and sharp dip angle, the stress arch is symmetrical arch in strike and asymmetrical arch in dip angle
	Burial depth	When the shallow coal seam is mined, the bearing capacity of the arch is lost after it extends to the surface. The arch structure will persist when the depth reaches a certain level
Application	Ground pressure prediction of working face	It can calculate the working resistance of hydraulic support and predict periodic weighting
	Roadway layout	Roadway layout inside the arch structure range
	Prediction and control of surface subsidence	The subsidence range and maximum subsidence value can be calculated according to the fracture arch; The surface subsidence rate and fracture development pattern can be predicted according to the periodic instability of the unconsolidated layer arch
	Roof aquifer control	Ensure that the maximum roof fracture arch height is below the aquifer
	dynamic disaster control in coal mine	The instability of far-field stress arch is the main cause of rockburst, and the roof pre-fracturing should be carried out in the peak area of stress arch
	Optimization of gas drainage technology	Gas extraction drilling holes should be arranged in the pressure relief area under the stress arch
Research focus	Theoretical research	Complicated stress boundary conditions, rock layer heterogeneity, irregularity of arch line, and the unequal thickness of the arch should be considered in the arch structure model
	Numerical simulation	Application of finite discrete elements or coupling of multiple simulation methods
	Similar simulation	Update of stress monitoring methods
	Field measurement	Overburden migration monitoring methods of space–sky–surface integration

Theoretical modeling, numerical simulation, similarity simulation, and field measurements have been used to study the overburden and unconsolidated layer arch, and rich results have been obtained, which have been applied to mine pressure prevention and mining subsidence control. According to the research methods, there are still some problems in the research process of the overburden and unconsolidated layer arch: (1) The theoretical model can provide the arch trace equation and then judge the bearing characteristics of the arch. However, there are some problems, such as the simplification of boundary stress conditions (mainly neglecting the abutment stress inside the arch), homogeneity assumption of strata, assumption of arch trace, and arch thickness calculation (the thickness of arch is not consistent). (2) Numerical simulation can readily provide the arch location, arch thickness, and evolution characteristics of the arch, but the stress arch simulated by a finite element ignores the influence of rock fracture, while the stress or fracture arch simulated by a discrete element depends on the division of blocks. The interaction between the unconsolidated layer and the overburden is rarely studied in the simulation process. The simulation method based on finite discrete element method (FDEM) can be used to simulate the arch of the overburden and unconsolidated layer. (3) Similar simulation can only qualitatively observe the development characteristics of the fracture arch, and it is difficult to determine the stress arch range. In future research, more effective stress monitoring methods with wider coverage is needed. (4) The field measurement is still focused on the borehole point monitoring at the height of the “three zones” of overburden rock, which only approximates the height of the fractured arch, and cannot detect the arch trace. Transient electromagnetic techniques and other methods, with which the accuracy is low, can only provide a rough range. In the future research, the migration characteristics of the arch can be comprehensively judged based on the space–sky–surface cooperative observation data, such as surface subsidence and movement, migration detection of deep base point of overburden, and mine pressure data of the working face [102].

The purpose of studying overburden and unconsolidated layer arches is to master the migration and fracture law of overburden induced by mining; on this basis, mining problems such as mine pressure in working face, height of the water-conducting fracture zone, pressure relief gas migration, and surface subsidence can be predicted. However, the application of overburden and unconsolidated layer arches focuses on the evolution law of arch structure, and there are relatively few active control methods for the overburden arch. Based on this, the overburden and unconsolidated layer arch control methods are divided into three categories: (1) Preset arch structure method before coal mining, including mining technology (filling mining, room and pillar mining, strip mining), mining parameter (mining height, working face length, advancing speed) design; The author has discussed this technology in detail in the literature [103,104]. (2) Process control arch methods during coal mining, e.g., grouting reinforcement arch protection (separated layer grouting, goaf grouting). Specifically, the arch trace equation under specific mining conditions can be calculated in advance to further provide the judgment conditions for arch fracture and stability. The grouting reinforcement area is proposed to ensure the stability of rock strata. In addition, some mining areas have thick and hard roof rock strata, and it is difficult to break the stable arch structure formed in the mining process, resulting in a dynamic risk. Under this condition, roof fracturing and arch breaking (hydraulic fracturing, deep hole blasting) are required to release the accumulated energy. (3) End reinforcement control arch methods after coal mining, in order to prevent and control the disturbance and instability in the reuse process of coal mine goaf, or the ground uplift caused by the rise of underground water level [105,106], arch grouting reinforcement is carried out for the goaf to prevent surface deformation and movement. As shown in Figure 10, the ground grouting holes surround the top boundary of the fracture zone in the goaf, and the boundary holes are arranged on the edge of the subsidence area to form the arch foot by grouting. The middle hole is located in the bending subsidence zone, and the grouting range is shown in Figure 10. According to the literature [99], the spacing of the grouting holes in goafs can be calculated with Equation (3).

$$a = 2R - \Delta b, \Delta b \geq F_s \frac{P_{\max}}{\sigma_c} \tag{3}$$

where: Δb is the spread width (m) of the grouting body; F_s is the safety factor, generally greater than 1.0; $P_{\max}$ is the maximum pressure of the overlying rock and soil layer (kN); σ_c is the compressive strength (kPa) of the grouting stone body.

There is relatively few reports and research on post-mining arches in coal mines. With the proposal of the strategy of carbon neutralization and carbon reaching peak, coal mining transformation is imperative in China, and the research focus on the abandonment mine ecological restoration and the space utilization of goaf will become a research hotspot [107–109]. Therefore, the future research on overlying rock arches in coal mine goafs mainly involves three aspects: (1) Determination of the arch structure location in coal mine goaf and its long-term (ten years and above) stability judgment. (2) After the mine is closed, due to no drainage, the water level of the goaf rises, long-term flooding and water level uplift are very important to the stability of the overlying arch. (3) The influence of engineering disturbances, such as pumped storage power stations, underground storage, engineering research center, surface industrial tourism, and ecological restoration on the stability of goaf arches in the process of mine reuse should be focused on.

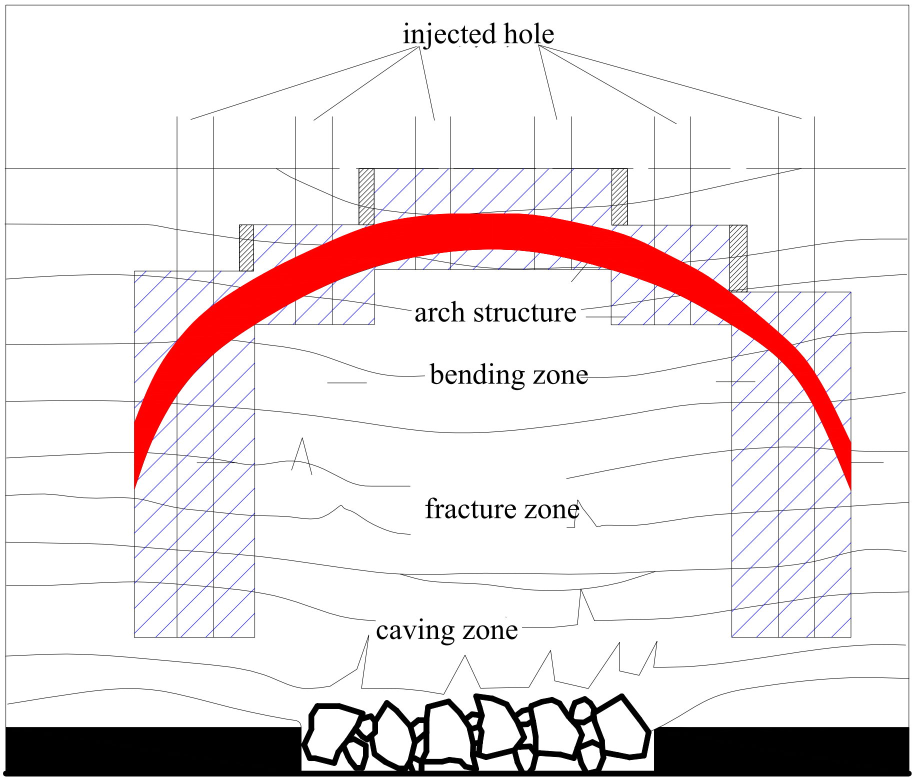

Figure 10. Schematic diagram of arch structure grouting in goaf.

7. Conclusions

(1) In order to fully understand the conduction mechanism of mining damage, the current research results of overburden movement are systematically reviewed with the arch structure model, and the research results are divided into the unconsolidated layer arch, beam arch, and overburden arch, according to the differences in characteristics of overburden combination and medium. The unconsolidated layer arch is proposed according to the condition of the thick unconsolidated layer. The beam arch is proposed for a single layer of thick hard rock. The overburden arch is proposed for the whole overburden structure, which is divided into stress arch and fracture arch.

(2) The existence of the overburden arch and unconsolidated layer arch was verified by theoretical model construction, numerical similarity, and simulation analysis. The morphological distribution and spatial evolution law of arch structure was provided, as well as the conditions of arch formation and arch breaking. The influence of mining parameters, lithology, dip angle, and mining method on the development of overburden arch structure was analyzed. On this basis, the working resistance calculation of working face support, the prediction of working face pressure, and the analysis of surface movement and subsidence were realized.

(3) The arch theoretical model of overburden and unconsolidated layers can provide the arch trace equation to judge the bearing characteristics of the arch. However, there are some limitations, such as simplification of boundary stress conditions, homogeneity assumption of strata, assumption of arch trace, and calculation of arch thickness. Numerical simulation can readily provide the location, thickness, and evolution characteristics of arch, but the stress arch simulated by finite element ignores the influence of rock fracture, while the stress or fracture arch simulated by discrete element depends on the division of blocks. The similarity simulation can only observe the development characteristics of fracture arch qualitatively, and it is difficult to determine the stress arch range. The field measurement mainly verifies the development characteristics of the fracture arch indirectly, through the development characteristics of the fracture zone.

(4) The application of overburden and unconsolidated layer arches focuses on the prediction and prevention of mine pressure and surface subsidence through the arch evolution model, and there are relatively few means to actively regulate the overburden arch. Thus, three control methods of arch structure in the underground coal mining were proposed: preset arch structure method before coal mining, process control arch methods during coal mining, and end reinforcement control arch methods after coal mining. Based on the current energy policy of China, the present paper puts forward the problems that may be encountered in the reuse process of abandoned mine: long-term stability, the impact of water immersion and water level rise, and engineering disturbance.

(5) Future research on arch structure modeling should focus on the following aspects: ① In the theoretical research, the support stress inside the arch should be considered in the stress boundary conditions. The heterogeneity of rock stratum and the non-uniformity of arch thickness should be considered. ② In the numerical simulation, the interaction between unconsolidated layer arch and overburden arch can be realized by finite discrete elements or coupling of multiple simulation methods. ③ In the similar simulation, the evolution method of stress arch can be obtained using the optical fiber method. ④ In field measurements, multiple methods designed for the space, sky, and surface can be used to monitor overburden migration characteristics.

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