Coal Wall Instability Evolution Law of Large Mining Height Face in Steeply Dipping Hard Roof Soft Coal Seam

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The coal wall of large mining height longwall fully mechanized face in steeply dipping coal seam has poor self-stability and high probability of instability, which is likely to induce secondary hazards such as support instability and flying gangue once catastrophic occurs, increasing the difficulty of surrounding rock control and production risk. Coal wall disaster prevention and control can improve the productivity of this type of face, and this is based on the sufficient understanding of damage patterns such as internal and external dispersion of coal wall pressure, deformation, and displacement; in order to clarify the coal wall dynamic failure law of large mining height face in steeply dipping coal seam, numerical calculation, field measurement, theoretical analysis, and other methods are comprehensively applied to the study. The results show that the coal wall bearing of large mining height face in steeply dipping coal seam is distributed asymmetrically, the stress concentration position in the upper and middle part of the face is closer to the coal wall than the lower part, the stress concentration degree is also larger than the lower part, and the stress concentration coefficients from upper to lower are 1.37, 1.50, and 1.29, respectively. Soft coal wall bearing is mainly dispersed in the shape of “X” in its interior, forming intertwined pressure increasing and unloading zones, and most of the pressure increasing zones are at the edge of the outer end of the pressure relief zone, compression-shear type is the main failure form of the coal, and the middle and upper part of the coal wall in the height direction is easy to break and cause disaster. The coal wall of steeply dipping face partitioning migration features is obvious, and vertical displacement within 3.77 m from the coal wall is lower > middle > upper; after 3.77 m, it is upper > middle > lower; horizontal displacement is middle > upper > lower; coal migration volume in the middle region of the face is largest; and the coal wall instability has high frequency, wide influence area, and alternating evolution law.

1. Introduction

Steeply dipping coal seams (shortly SDCS) are widely distributed in the mines in western China; such coal seam is of good quality and large angle, and most of them are thick coal seams. With the innovation and improvement of large mining technology and complete equipment, large mining technology has been initially applied in steeply dipping thick coal seam mining, such as 25221 face of Xinjiang 2130 mine and 4238 face of Huashan mine. Coal wall of large mining height face in steeply dipping (shortly LHSD) has large wall height, wide migration space, complex bearing environment, and high probability of disaster caused by the evolution of mining dynamics. The primary and secondary cracks continue to develop during the bearing process of the coal in front of the face, and the coupled cutting effect will induce coal wall catastrophe, the essential of surrounding rock catastrophe control in the SDCS being the “roof-support-floor”(shortly “R-S-F”) system dynamic stability control [1]. Different type catastrophes mostly have linkage under the condition of steeply dipping, and coal wall catastrophe is easy to cause diversified dynamic disasters such as roof caving and support dumping, resulting in the failure of pressure system and aggravating the disaster of surrounding rock. It can be seen that coal wall disaster will seriously restrict the safe production of LHSD.

Large mining height has obvious advantages such as high recovery rate, less resource waste, and safety, for steeply dipping thick coal seam with good mining conditions and
resource quality, while this kind of face has great dip angle and large mining height, which makes coal wall extremely vulnerable to disaster. In order to solve the problem of large mining height mining in steeply dipping thick coal seam, many scholars have studied this kind of face from different aspects. Literature [2–6] deeply studied the overburden failure modes, stress field, and evolution characteristics and constructed the "R-S-F" system dynamics model and equation, so as to determine the support resistance of the system to maintain stability. Literature [7, 8] studied the surrounding rock migration law and the support effect of large mining height in SDCS. Literature [9, 10] studied the support stability of large mining height in SDCS. Literature [11–13] constructed the coal wall bearing mechanical model of large mining height face by the slope analysis method, pressure bar theory, and mises criterion. Literature [14] studied the coal wall spalling mechanism of fully mechanized mining face in steeply dipping thick coal seam under close goaf. Literature [15, 16] obtained the coal wall stress, deformation characteristics, and spalling mechanism of LHSD. Literature [17] studied the coal wall spalling characters and preventive technology of LHSD. Literature [18] studied the coal wall failure law of complex thin coal seam face. Relevant literature studies show that the research on mining of SDMS mainly focuses on general mining height and fully mechanized top caving face and mostly studies on overburden movement, stress field distribution, interaction mechanism between support and overburden, and large mining height as a new technical development direction of mining SDCS. The related research is still not in-depth and focuses on overburden movement pattern and support stability. Coal wall mining behavior is a restrictive factor of safe mining of LHSD, although it has attracted the attention of some scholars and achieved some results. It is mostly concentrated on large mining height face with nearly horizontal and other small inclination angle, and the related research mainly focuses on the coal wall spalling mechanical analysis model, mechanism, and control. There is a lack of research on the evolution law of coal wall bearing internal and external dissemination and instability formation of LHSD. Clarifying coal wall dynamic failure law can provide the reference and basis for the coal wall catastrophe control under similar mining conditions. Therefore, this paper takes the large mining height face of SDCS as the background to systematically study the instability evolution laws of coal wall bearing formation, spatial distribution, internal spreading and transmission, and pressure response behavior.

2. Study Background

A face strike length is 1813 m, tendency length is 105 m, coal seam thickness is 3.58–9.77 m, with an average of 5.77 m, coal seam dip angle is 36°–46°, with an average of 44°, bulk density is 1.39 t/m³, and hardness coefficient f is 0.3–0.5. The roof of the coal seam is pebbled medium sandstone with a compressive strength of 62.56 MPa, and the floor is gritstone with a compressive strength of 9.14–12.76 MPa. Face adopts the strike longwall mining method, the mining height is 3.5–4.8 m, and it is a typical LHSD.

3. Dispersion Law of Coal Wall Bearing of LHSD

3.1. Formation and Distribution Law of Coal Bearing of LHSD

The collapsed gangue of LHSD tends to slip and fill the lower goaf due to the self weight and other components under the dip angle effect, resulting in regional alienation of the filling condition of the goaf, and the filling degree of lower and middle airspace are larger than upper (Figure 1(a)). The filling efficiency of the goaf is different, resulting in different spatial scales of rock migration. The accumulation and compaction rate of gangue in the middle and upper are low, which can provide necessary space for the full migration of overburden. High level rock can be disturbed during the migration process of low level rock near the face, making the strata movement level rise and enlarging the control range of overburden. Rock may crush and impact with each other to form roof pressure in which distribution is regional asymmetry during the rock migration. The contour presents an asymmetrical arch, and the vault is located in the middle and upper part of the face (Figure 1(b)).

The overburden migration of LHSD is accompanied by stress dissipation and release, and there is a negative correlation between strata migration and stress unloading, namely, the more sufficient rock migration, the greater the stress reduction. The nonuniform filling of goaf of steeply dipping face, rock migration in the lower area is restricted, stress cannot be released in time and adequately. It will accumulate under the action of continuous mining to form a high-strength concentration area. The upper and middle airspace is relatively sufficient, the damage degree of overburden increases, and the release of stress increases after consumption, so the overburden stress of LHSD is distributed in zones. The numerical calculation results of stress and displacement (Figure 2(a)) show that the middle and upper regions stress intensity < lower. The stress distribution in the overburden is closely related to the migration and transformation of roof pressure, and the main way that can cause stress change is the damage of the overburden such as migration. A significant reduction of stress indicates a large degree of strata, while the mechanical action of discrete degraded strata will be transmitted to the lower strata and supports. According to the field support resistance monitoring data of LHSD (Figure 2(b)), the main concentration range of support resistance in the lower part of face is 1500–4500 KN. In the middle and upper parts, 51% and 73% of the support resistance exceeds 4500 KN, respectively, and the support resistance distribution is shown as middle and upper > lower. Therefore, the roof pressure in the middle and upper of LHSD > lower.

The coal wall bearing of LHSD is closely related to the distribution of roof pressure and the filling state of the goaf. The roof of the face is hard and has high load transfer performance, so roof pressure is transferred to the coal wall through the roof rock beam and forms an abutment-pressure disturbance zone in front of the coal wall. Irregular filling of the goaf makes the coal wall coupled with different media in each area of the face, thus forming a regional dissimilar pressure-bearing system. The lower goaf has a high degree of gangue filling and a small space for the
movement of broken gangue. It will evolve into a pressure bearing structure that exhibits roof control efficiency during overburden migration and interact with the support and coal wall to form a “gangue-support-coal wall” pressure bearing system. Although a large amount of gangue will be accumulated in the middle airspace, the overall compaction rate is low, and the roof control ability of gangue is limited and weakened, so the roof of middle and upper part are mainly controlled by coal wall and support due to insufficient gangue filling in the goaf. The combined effect of asymmetric roof pressure and partitioned bearing structure causes the asymmetrical partitioned bearing of coal wall of LHSD (Figure 3).

The effect of abutment pressure in front of the coal wall varies in different areas of LHSD. The bearing strength at the coal wall is 4.36 MPa, 5.23 MPa, and 3.67 MPa from upper to lower, respectively, with the distribution characteristics showing that the middle is the largest, the upper is the second, and the lower is the smallest. The asymmetric bearing pressure of the coal makes the peak position different in each area, and the position of upper and middle part of the face is closer to the coal wall than the lower part.

Figure 1: Overburden failure characteristic of LHSD. (a) Collapse morphology. (b) Mechanical distribution.

Figure 2: Mechanical distribution characteristic of LHSD. (a) Rock migration characteristic curve. (b) Support resistance.

Figure 3: Curve of numerical calculation results of coal wall stress of LHSD.
The middle and upper part is 2.8 ~ 4.7 m ahead of the coal wall, while the lower area is concentrated at 5.7 ~ 6.6 m in front of the coal wall, the peak abutment pressure strength is 4.87 MPa, 7.14 MPa, and 5.70 MPa from upper to lower, the small amount of stress variation outside the stress disturbance zone can be considered as the original rock stress, so the original stress is 3.55 MPa, 4.76 MPa, and 5.81 MPa. Although peak abutment pressure strength distribution is lower in middle and upper areas, the stress evolution range in each region of the coal after mining is opposite, and the corresponding ballast concentration (pressurization) coefficients are 1.37, 1.50, and 1.29 in turn. The analysis shows that, in the mining process of face, the disturbance efficiency of mining action on the coal wall and the front coal bearing is regionally alienated. The bearing concentration of the coal in middle and upper areas is more significant, and the drastic change of the bearing environment is likely to induce the rapid destruction of the coal. It can be seen that the coal wall stability in the middle and upper region of LHSD is worse than that in the lower area.

3.2. The Law of Pressure Spreading inside the Coal Wall of LHSD. The coal bearing of LHSD will spread in multiple dimensions. When the bearing is distributed ahead of the coal wall in the strike, it will also be transmitted from the coal to floor in the vertical. The coal as the key body in the vertical propagation process has the dual role of bearing and transmitting pressure, with the removal of the mechanical constraint on the free side of the coal wall, and it will be in a similar single bearing compression state under the clamping of the roof and floor. Due to the influence of the heterogeneous and anisotropic material properties of the coal body, the stress is irregularly distributed inside the coal wall, and the small-scale stress concentration influence zone is first formed in a small local range, where stress intensity zoning is evident; specifically, it can be divided into pressure relief (pressure drop) zone and accumulation (pressure increase) zone, and the accumulation zone is located at the edge of the pressure relief zone (Figure 4), which indicates that the compressive stress will first concentrate in the weak structure of the coal body, forming a high-strength mechanical effect; pressure drop occurs with the destruction and dissipation of the coal body and then transfers to the adjacent coal body. The rupture of the pressure relief zone evolves into a weak structure, which makes the stress reconcentrate around this area, showing the interwoven phenomenon of depressurization and pressurization zones.

The stress concentration affected zone in the coal wall of LHSD is initially scattered in the vertical middle and upper end vicinity of the coal body in the shape of "1," and the concentration zone is symmetrically distributed on the left and right sides of the pressure relief zone. The number and disturbance range of pressure relief zones are small (Figure 4(a)). With the nonlinear dispersion of stress within the coal body, the concentrated stress concentration affected zone gradually expands, and the number of pressure relief zones increases significantly. The scale of the concentrated influence zone varies at different locations, and the dispersion range of upper and middle unloading zones is large, among which the upper end is the most widely distributed. The distribution pattern of the stress concentration affected zone is similar to the X-shaped radial (Figure 4(b)), and this form is the main form of stress continuous and alternate dispersion in the coal body so that the scattered concentrated stress action zones gradually blends with each other to form a continuous pressure drop zone. However, the appearance of the pressure relief zone is different after blending at different positions, the "M" type compressive stress reduction zone will be formed in the middle and upper part of the coal body, where the degree of stress reduction and dispersion range within the pressure relief zone are greater than other locations, while the middle and lower part of the coal body is presented in an inverted “L” shape, and its lower trace tends to form an angle of nearly 45° with the lower end face of the coal body (Figure 4(c)). The distribution of coal bearing strength in the unloading zone gradually decreases from the outside to the inside, and its evolution shows an overall decreasing trend, that is, the stress intensity at the same position will decrease because of the continuous consumption of the development of coal damage, and the stress drop is the largest and the strength value is the lowest in the fracture neighbourhood. With the internal rupture of the coal body, the bearing environment of the coal around the part of the pressure relief zone will change, from a single compressive stress state to a composite state of compressive and tensile stress; especially the area adjacent to the end of the pressure relief zone is prone to the formation of the tensile stress concentration zone. The stresses in the accumulation zone evolves in the form of "first rising and then falling", which is manifested as the gradual increase before the coal fracture and the significant decrease after the fracture.

The location, evolution form, and scope of the stress concentration affected zone inside the coal wall of LHSD are closely related to its continuous bearing effect and bearing traits. Stress is unevenly distributed within the coal wall. It mainly spreads alternately in the "X" shape interlaced pressure relief zone and accumulation zone. The concentrated stress is continuously released in the process of promoting the deformation and rupture of the coal body; thus, the coal bearing in the pressure relief zone shows a declining evolution trend. As the bearing capacity of the coal in the unloading zone decreases, stress will reconcentrate at the edge of the unloading zone, and the strength of the action will gradually increase; after the rupture of the coal, the pressure transmission efficiency is greatly weakened, and the stress release is relatively sufficient, resulting in stress accumulation at local positions, but the action intensity is obviously low, so the evolution form of the bearing of the coal in the accumulation zone is "rising first and then falling." The distribution and evolution of stress concentration affected zone is the result of the continuous bearing action, and the key influencing factor is the bearing action time, from the stress evolution characteristics of the coal wall. It can be seen that, with the extension of the action time, the stress will continue to accumulate in the coal body within the direct action range and aggravate the destruction.
of the coal body, and the stress action range is greatly expanded. For the mining face, mining speed can determine the pressure bearing time of coal wall and the front coal, so the mining speed is negatively related to the pressure-bearing property of the coal wall; to a certain extent, accelerating the mining speed can shorten action time of the advanced abutment pressure on the coal wall, reduce the concentration extent within the coal wall, and improve the stability of coal wall.

The stress form of the mechanical concentration affected zone in the coal wall of LHSD is mostly compressive stress. Although tensile stress will appear locally after coal ruptures, the influence range and concentration degree are small, so the soft coal rupture is mainly caused by the action of concentrated compressive stress. The area near the upper end of soft coal forms a pressure relief zone with wide area and full stress release, and the coal body is relatively broken, while the middle and lower part forms an "L" type belt pressure relief zone extending from the middle to the lower end, cutting the coal structure in the vicinity of the lower end. The bearing release effect of the coal in the upper part is obviously more prominent than other parts, and the stress release is closely related to the stability state of the coal, that is, the stress is fully released, the accumulated amount of coal wall damage is large, and the extent of internal structure deterioration is high. Therefore, it can be seen that the middle and upper of the soft coal wall of LHSD is more prone to deterioration and instability.

4. Evolution Law of Coal Wall Failure of LHSD

Coal wall instability of LHSD is a macroscopic damage phenomenon caused by the qualitative change of composition structure which is induced by the quantitative change of coal deformation, displacement and other pressure-bearing behaviors, and the internal structural deterioration that leads to the gradual evolution of the overall medium state of coal body into loose and broken state, the significant weakening of pressure-bearing efficiency, and then the large scale migration. Therefore, it is necessary to systematically study the dynamic damage law of coal wall from the three aspects of coal wall bearing deterioration, migration, and instability area distribution.

4.1. Coal Wall Deterioration Law of LHSD. During the process of the change of coal wall properties of LHSD forced by the continuous action of advance abutment pressure, the pressure energy is formed and gradually accumulated to the extreme value, which induces the phenomenon of acoustic emission. The nonuniform distribution of stress in the coal wall causes the variation of acoustic emission at different locations of the coal wall in the height direction (Figure 5(a)), and the acoustic emission intensity in the middle and upper neighborhood is higher than the rest of the locations, which is characterized by frequent occurrence and wide distribution. It basically covers the whole middle and upper part of the coal wall in the form of "M." The lower part forms a single oblique belt type acoustic emission area with an inclination of nearly 45°, and the contour trace of the affected area is in the "L" shape linear state. However, the form of acoustic emission evolution is similar, and all of them develop and extend in different degrees in "X" radial shape and interweave, forming a heterogeneous acoustic emission intensive area, which closely mirrors the distribution and evolution form of stress concentration affected area. Therefore, it can fully explain that the compressive stress disperses and evolves in "X" shape inside the soft coal wall.

The main damage of coal wall of LHSD is compression-shear failure, but the deterioration forms at different vertical positions are different (Figure 5(b)). The damage in the middle and upper part of the coal wall is the most serious, the fractures are fully developed in multiple dimensions, the structure of the residual body is highly discrete, the shape is relatively broken, the fragmentation of the broken body is small, the deterioration area is widely
dispersed, the damage area has a downward spreading trend, and the overall appearance of the damage area is "M" shape. The lower end neighborhood mainly suffers from monoclinic fracture developmental damage, with a limited influence range. The coal body structure is relatively complete, the lateral volume expansion is obvious after the coal rupture, and the increment decreases from upper to lower. The analysis shows the influence of the material properties of the soft coal wall of LHSD, the inherent pressure-bearing capacity of the medium is low, the coal in the middle and upper part of the coal wall is pressed for a long time, and there is a large accumulation of internal structural damage, which causes the coal in this area to be more loose and fragmented. The pressure bearing efficiency is greatly weakened, and then the deformation mode of the coal transitions from compression state to volume expansion, showing the phenomenon of alienated volume expansion at different positions. For the mining face, the constraint of the coal wall adjacent to the goaf is eliminated, which makes the lateral deformation of coal mainly develop into the goaf, thus showing the phenomenon of convex movement. The evolution results of coal wall mining behavior (Figure 5(c)) also show that, during the mining process, most of the instability positions of the coal wall are concentrated in the middle and upper neighborhood, and the convex migration amount and distribution range of the coal wall are large. It can be seen that the prone positions of coal instability are basically the same at different scales. Therefore, the middle and upper part of the soft coal wall in the height direction of LHSD should be the key prevention and control area of instability, and its failure degree is dynamically related to the time effect, so the mining speed can be adjusted appropriately to ensure the coal wall stability.

4.2. Coal Wall Migration Law of LHSD. The migration of the coal wall and the coal ahead of the coal wall of LHSD is the result of the dynamic equilibrium distribution and evolution of the abutment pressure. Under the inclination effect, the pressure-bearing environment of coal body is regionally different, which makes movement of the coal wall and front coal body of LHSD also change in intervals, and the migration forms are different.

Vertical displacement (Figure 6(a)) varies at 3.77 m in front of the coal wall, coal displacement in the range of 0~3.77 m is lower > middle > upper, and after 3.77 m, it is upper > middle > lower. The analysis shows that the filling degree of lower goaf of this coal seam face is high, so the free movement space of coal and rock is small, and roof pressure is not easy to be fully and effectively released in time, resulting in large scale vertical movement in the coal near the coal wall after loading. Combined with the coal wall mechanical properties, it can be seen that the greater the coal migration, the weaker the bearing capacity of the coal near the coal wall, the larger the distance of abutment pressure transfer in front of the coal wall and the farther the location where the mechanics is concentrated and reaches its peak. Stress transmission process is also its release process, with the increase of the propagation distance in the coal. The action intensity and displacement of the coal can decrease in varying degrees, the 3.77 m in front of the coal wall is located in the stress concentration area in the upper and middle part of face, the loading of the coal in this area increases obviously, and the extent of stress concentration is very high. Coal is prone to large scale displacement, and the value is obviously higher than that of coal in the lower face. This makes 3.77 m become the inflection point of coal migration volume change and presents different zonal migration features on both sides.

Horizontal displacement (Figure 6(b)) changes more evenly, and the overall displacement is middle > upper > lower, while the horizontal displacement can reflect the migration of coal wall and its front coal to the side of the goaf. The larger the coal migration amount, the greater the probability of the coal breaking away from the coal wall. Based on the analysis of mechanics distribution and migration characteristics of LHSD, it can be seen that the instability of the coal wall is likely to occur in the middle and upper part of the face, especially in the middle area.

Figure 5: Coal damage characteristic. (a) AE distribution. (b) Displacement characteristics. (c) Instability position.
4.3. Distribution Law of Coal Wall Instability of LHSD.

The location, scope, and frequency of coal wall instability of LHSD are obviously regional alienation (Figure 7). During the field measurement, the coal wall spalling instability of LHSD occurred many times with different degrees, and the frequency of coal wall instability reached 2~4 times in some daily monitoring periods, which shows that the coal wall instability of this kind of face has high frequency. When the coal wall instability of LHSD is serious, the affected area is almost all over the whole face, but the probability of such damage is low. Instability occurs mainly in the form of randomization, with a wide influence range, and the main areas of instability are concentrated in the middle and upper of the face, especially in the middle, it is the most serious. The numerical calculation data of coal displacement also shows that the displacement of the middle and upper is larger than the lower, and the overall displacement in the middle is relatively large. The measured distribution of coal wall instability is highly consistent with the numerical calculation displacement results, so it can be seen that the key area for the prevention and control of coal wall instability of LHSD is the middle and upper area, especially the middle of the face, where the occurrence probability and scope are large.

The instability range of coal wall in the middle of LHSD is mostly more than 1/2 of the length of the area, and the frequency of occurrence is high. This area will also basically occur instability when instability in other areas, followed by the upper area, which mostly occurs in the range of 40~50# intersupport. Although the coal wall in the lower area will also be unstable, the frequency and influence range are small, and the instability mainly occurs in the area between 15# and 20# supports, indicating that the instability of the coal wall in the upper and lower of the face mainly occurs in the vicinity of the boundary with the middle area. The analysis shows that the nonuniform filling of gangue in the goaf with large dip angle and more significant in the neighborhood of regional boundary, causing the sudden change of coal wall bearing environment and the formation localized concentrated ballast, thus prompting the rapid development and expansion of coal damage in the domain, showing the characteristics of high frequency, wide area, and zonal distribution. In addition, the coal wall will be alternately destabilized, that is, before and after the face advances. The position and range of the coal wall instability on the tendency evolve with negative correlation.

There is always an advanced abutment pressure influence zone in front of the coal wall of LHSD, and the strength of the action is far more than the original rock stress. The abutment pressure action is easily superimposed before and after mining, so that the coal near the coal wall is in a high pressure environment, and its internal structural damage continues to accumulate, which induces the development and expansion of the primary and secondary fractures and forms a precracking effect on the coal body near the coal wall. As the new coal wall is exposed by face advancing, coal bearing environment suddenly changes to the state of "unloading lateral pressure—adding axial pressure"—resulting in the jumping change in the properties of the coal wall and large-scale migration to the goaf and breaking away from the coal wall. The coal wall damage condition is closely related to the degree of bearing release and has a positive correlation. When the coal wall is unstable in a large range, the concentrated force can be fully released by a large amount of consumption, which can reduce the pressure of the coal body in front of the coal wall in the same area to a certain extent, so that the instability degree of the coal wall is reduced. The instability position is transferred, and the distribution range is reduced after the face is advanced. However, the bearing of the coal body in the area where instability did not occur will be
superimposed many times, which promotes the expansion of the instability range and shows the characteristics of alternating instability. Under the mining condition of steeply dipping, the dip effect causes nonuniform filling in the goaf of the face. Due to the low filling rate of gangue in the middle and upper area, the “support-coal wall” is used as the main structure to control the roof, and the coal wall bearing strength increases. In addition, the roof collapsed layer in this area is high, the strength of roof pressure is also high, the coupling effect of the strong roof pressure and the main control body of the roof promotes the coal wall regional instability and mostly occurs in the middle and upper area of the face.

5. Coal Wall Bearing Analysis of LHSD

Roof of 25221 LHSD is hard, while the coal is very soft and its strength is lower than that of roof and floor strata. Therefore, coal can be regarded as the soft interlayer between the hard rock mass. According to the coal wall bearing and damage evolution laws of face, it can be seen that the coal wall and coal in front of it is always subject to ballast during the face mining, so that compression-shear failure occurs in the coal and forms broken body and then breaks away from the coal wall to form spalling instability. Therefore, coal wall bearing of LHSD can be simplified to the mechanical model of interlayer compression and extrusion (Figure 8). The microelement is taken along the strike of face, thickness is \( dx \), height is \( h \), the compressive stress acting on the microelement is \( \sigma_x \) and \( \sigma_z \) and the stress in the \( x \) direction has irregular variability, so the influence of thickness \( dx \) cannot be ignored. The stress at the position of \( dx \) is \( \sigma_x + d\sigma_x \), the friction stress between coal and roof (floor) is \( \tau \), and dip angle of coal seam is \( \phi \).

According to the stress equilibrium condition, the \( x \)-direction stress equilibrium equation can be obtained:

\[
\begin{align*} 
\int h \sigma_x + 2 \tau \, dx - h (\sigma_x + d\sigma_x) &= 0, \\
\int h &= \frac{M}{\cos \phi}, \\
\tau &= \sigma_z \tan \theta + C, 
\end{align*}
\]

where \( M \) is the mining height, \( m \); \( \theta \) is the friction angle of coal-rock interface, °; and \( C \) is the cohesion of coal-rock interface, MPa.

After simplification, the following can be obtained:

\[
\begin{align*} 
\frac{d\sigma_x}{dx} &= \frac{2(\sigma_z \tan \theta + C) \cos \phi}{M}, \\
\sigma_z - \frac{1 + \sin \theta}{1 - \sin \theta} \sigma_x &= \frac{2 C \cos \theta}{1 - \sin \theta}, \\
\text{Calculate equation (3):} \quad \frac{d\sigma_x}{dx} &= \frac{d\sigma_z}{\tan^2 (\pi/4 + \theta/2) \, dx}. 
\end{align*}
\]

Substituting equation (4) into (2), we obtain
\[ \sigma_z = C \cdot e^{\frac{2\tan\theta\tan^2(\pi/4+\theta/2)\cdot\cos\phi}{M_\sigma M_x}} - \frac{C}{\tan \theta} \]  
\hspace{1cm} (5)

According to the coal wall bearing model shown in Figure 8, the corresponding boundary condition is \( \sigma_x (x = 0) = 0 \). Combined with equations (3) and (5), we obtain

\[ \sigma_z = \frac{2\sin \theta + (1 - \sin \theta)C \cdot e^{\frac{2\tan\theta\tan^2(\pi/4+\theta/2)\cdot\cos\phi}{M_\sigma M_x}} - \frac{C}{\tan \theta}}{(1 - \sin \theta)\tan \theta} \]  
\hspace{1cm} (6)

Roof pressure can transfer to the coal wall through the overburden and other force transmitting medium during the extraction of LHSD, forcing the plastic deformation of coal near the coal wall to form a plastic zone. Equation (6) shows that the abutment pressure in front of coal wall exhibits an exponential distribution characteristic in the plastic zone, and it first acts on the coal near the coal wall, causing damage to the internal structure of the coal near the coal wall, expansion of cracks, and reduction of bearing capacity. Abutment pressure value is decreased to form residual abutment pressure at the coal wall, so that the abutment pressure moves forward and reaches its peak value at \( x \) away from the coal wall. Under the action of abutment pressure, coal wall can derive new cracks and extend with the primary cracks until the cracks intersect to form broken blocks, while it is difficult to form effective supporting force behind of the coal wall (near the side of the goaf) to balance the destructive force, thus forcing large-scale displacement of broken blocks to break away from coal wall and causing macroscopic spalling failure. Face angle of SDSCS is large, and the forces such as roof pressure and weight of broken blocks are easily decomposed to form a tendency component. However, the coal wall lacks effective support in this direction, and the broken blocks of coal wall can gradually evolve into sliding blocks and migrate in the tendency, resulting in coal wall sliding which is the special catastrophic mode of coal wall in large mining height face with SDCS.

**6. Discussion**

Based on the mining background of LHSD, this paper constructs the mining model of large mining height in steeply dipping by using Flac\textsuperscript{3D} and 3dec software to study the bearing formation and spatial distribution law, migration law, and vertical instability position of coal wall. The RFPA software is used to study the dispersion and transmission law of bearing inside the coal wall and the form and location of coal wall failure. Through field measurement, the coal wall destabilization area, the impact range and the occurrence rate are clarified. Combined with the mechanical environment of coal wall, the coal wall bearing model is constructed after simplification to analyze the causes of coal wall instability of LHSD. The results of each methods are compared and analyzed to obtain the failure evolution laws of different dimensions such as asymmetric bearing of coal wall and regional alienation of migration of LHSD.

In this paper, both numerical calculation model and bearing analysis model are simplified to facilitate the research and analysis. Among them, the numerical calculation model is shown as follows: (1) the coal wall and surrounding rock are regarded as continuous media without considering the effects of layer interface parameters and distribution; (2) the two key elements of mining height and pseudoangle of this type of face are not studied, and the impact of mining height and pseudoangle on coal wall damage is not been quantified. The bearing analysis model does not consider the influence of coal wall weight and lateral force. However, layer effect, mining height, pseudoangle, self-weight, and other factors will affect the evolution of coal wall bearing and the mining behavior to varying degrees. The linkage mechanism between each factor and coal wall instability and the main control key factors for instability remain to be clarified. Therefore, the research on the evolution law of mining dynamic behavior such as coal wall bearing and migration of LHSD needs to be further deepened.

**7. Conclusions**

(1) Coal wall bearing of LHSD has regional alienation. The distribution of coal wall bearing is central > upper > lower, the stress concentration position in the upper and middle of the face is closer to the coal wall than the lower, the stress concentration degree is also larger than the lower part, and
the stress concentration degree in the middle part of the face is the largest. The stress concentration coefficient of each area is 1.37, 1.50, and 1.29, respectively, from upper to lower of the face.

(2) The bearing of the soft coal wall of LHSD is spread in the shape of “X” inside it, forming intertwined pressure increasing and unloading zones. The pressure-increasing area is located at the edge of the outer end of the pressure relief zone, and the coal in the vicinity of the upper end of the coal wall is broken in the “M” shape, with high degree of fragmentation and wide range of influence. The lower end is developed with an inverted “L” fracture at an angle of 45° for pressure relief, the tensile stress will accumulate around the local pressure-unloading zone after the coal is broken, compression-shear type is the main failure form of the coal, and the middle and upper neighborhood of the coal wall in the height direction is more broken than other parts.

(3) Coal wall partitioning migration characteristic of LHSD is obvious. Vertical displacement in the range of 0∼3.77 m is lower > middle > upper; after 3.77 m, it is upper > middle > lower; horizontal displacement is middle > upper > lower; coal migration volume in the middle region of the face is relatively large. Coal wall instability has the features of high frequency, wide influence area, and alternating evolution, which mainly occurs in the middle and upper of the face, and the middle is the most serious.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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