Instability mechanism of surrounding rock chain structure in steeply inclined thick seam mining

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Abstract. In view of the difficulty of fully-mechanized mining in steeply inclined coal seam with thickness of 4 to 8 m, the horizontal section short wall fully-mechanized caving mining method is innovatively proposed. In the No. 3-3c steeply inclined coal seam of a Coal Mine, the single roadway integrated with excavation and recovery is arranged as working face, the pillar on sides of roadway is recovered ahead by spiral drilling machine, and the top coal is recovered by the vertical and horizontal self-moving supports. The Z-type ventilation is formed by constructing a ventilation roadway along the side of gob. Through theoretical analysis, numerical calculation and physical similarity simulation, the main mining parameters, including sectional height and ratio of mining height to caving height, were determined, and the characteristics of roof movement evolution, floor failure and sliding and the generalization of surrounding rock bearing structure were revealed. The results show that the effect of coal caving is better when the section height is 10 m and the ratio of mining height to caving height is 2.85. The cross-layer multi-ladder voussoir structure is formed by transformation and migration of the critical layer, and the failure and slip modes of floor are extruding-translation, extruding-underdraught and extruding-upthrust in different areas of horizontal sublevel caving stope. Roof, pillar and floor are interrelated to form the Roof-Pillar-Floor (R-P-F) chain structure. When the height of section with three sublevels is 30 to 45 m, the mutual conversion of strong and weak chains between structural units can be cut effectively in mining process, and the impact disaster caused by the roof falling over great extent and the instability of pillar can be prevented. The new mining method proposed and studied above provides the technological and theoretical basis for the safe and efficient production of such coal seams, and is of great significance to the sustainable development of coal in Xinjiang province and even western China.

1. Introduction

A steeply inclined seam is that with a dip angle greater than 45°, which is abundant in Russia, Ukraine, Poland and other countries, as well as in the western and the southern coal-deficient area of China,
especially in Xinjiang[1]. Due to the large inclination of the coal seam, mining is extremely difficult. The traditional non-mechanized coal mining method is generally used in small coal mines that mine such steeply inclined seams, such as stacking, shrinkage stoping, heading-and-bench mining, roadway-caving mining, with low mechanization degree, large labor intensity, complex technology, poor working environment, difficult management, many safety accidents and low yield efficiency[2]. Since the 1970s, in the mining of steeply inclined coal seam, the medium coal mine has gradually tested the wire rope saw mining method, the flexible shield mining in the false dip, the segmented intensive pillar mining, overhand mining and so on, but there are still some problems such as high labor intensity and low output efficiency[3-5]. With the development of fully mechanized coal mining technology in the 1980s, large and medium-sized coal mine tests have succeeded in the horizontal section mechanized top coal caving method (referred to as fully-mechanized caving mining method) with steeply inclined extra-thick seam (above 10 m), which significantly reduced the labor intensity and significantly improved the safety and working environment[6-7]. However, the length of the working face is restricted by the thickness of the coal seam and the inclination angle, and the working face is forced to increase or decrease the support frequently, so it cannot advance normally. In recent years, in order to increase the production of horizontal section fully mechanized caving face in steeply inclined extra-thick seam, the method of increasing the section height to increase the thickness of top coal was tested. However, due to the formation of cross-layer arch, the increase of section height is restricted and the increase of working face output is still limited[8-9]. Over the past ten years, the technology of steeply dipping medium thick seam fully mechanized mining has become more and more mature[10-12], which has achieved good safety and economic benefits. When the inclination angle is less than 55°, thickness less than 4 m, the stability of the coal used to longwall fully mechanized, large mining height or fully fully-mechanized caving mining effect is good. But increases as the dip angle of the coal seam and working longer, top-coal difficult to control, the problem of support instability easily is particularly acute. Especially when the coal seam is loose, the top coal leakage intensifies and expands rapidly along the working face incline upward, resulting in the support group slipping, the working face production paralysis, the great difficulty in dealing with the roof fall and the inverted support accidents, the sharp increase of safety risks, and the abnormal difficulty in resuming production. Because the caving top coal slides and piles up in the lower gob of the working face, it cannot be released, which leads to the extremely low release rate of the top coal. Generally, the length of the long wall face is more than 80 m, the operation and management of the working face is very difficult, and with the increase of the length, the difficulty is abnormal, which often causes the working face to be unable to produce normally. For steeply inclined coal seams with a dip angle greater than 70° and a thickness of 3~5m, the mechanization of coal fall mode is realized by adopting backward milling machine with long wall pseudo inclined flexible shield support[13]. Nowadays, for steeply inclined thick seam with seam inclination greater than 55° and thickness of 4~8 m, the feasible mining methods include horizontal section fully mechanized caving mining and inclined slicing fully mechanized caving mining. However, there are some problems such as low mining efficiency, complex safety management and poor economic benefits. There is no reasonable safe and efficient mining method for mining this kind of coal seam at home and abroad.

In the mining of steeply inclined seam, roof breaking form, the height of collapse and floor failure and slip will be all change. The traditional theory of rock pressure cannot explain the above law of ground pressure behavior very well, domestic and foreign scholars have studied this and obtained some useful conclusions. When mining method is the horizontal section mining of steeply inclined extra-thick coal seam, the cantilever beam structure, the large structure of unequal height unloading arch and the articulated rock block structure formed in the inclined direction of the roof, which reveals the toppling-slip fracture mode and weighting process of overburden. It is found that the roof structure of the steeply inclined working face is stable and easy to control the impact caused by the sliding instability of the structure[14-15]. With the increase of section height of steeply inclined seam, the influence of upper section mining on the lower section is gradually weakened, and the larger thickness coal of the lower section acts as a buffer[16]. Asymmetric arch structure is formed by the combination of top coal and overlying residual coal and gangue and evolved into a typical inclined ellipsoid structure, which is prone
to local pressure distortion caused by sliding instability and induced dynamic disasters\cite{17-18}. Floor failure and slip is a time-space development process, which is affected by the geological and mining factors, and the critical mechanical condition of floor failure is given\cite{19}. According to the above research results, there is a comprehensive understanding of the roof structure form, the rock pressure characteristics and the floor failure and slip characteristics of different steeply inclined extra-thick seam, but the mechanism of the interaction between the roof, the coal pillar and the floor in the process of the surrounding rock disaster in the stope needs to be further studied.

Therefore, based on above difficult problem, taking the 3-3c steeply inclined thick coal seam of a coal mine in Xinjiang as the engineering background, the horizontal section short wall fully mechanized caving mining of a steeply inclined thick seam method is proposed innovatively, which forms the working face roadway system with the characteristics of integration of mining and excavation and Z type ventilation. The research reveals the generalization characteristics of stope bearing structure and chain disaster mechanism during the mining process, which lays a foundation for the safe and efficient mining of this kind of coal seam.

![Figure 1 Layout of main development roadways in a coal mine](image)

2. Engineering background
A mine is located in the north wing of Keerjian syncline 65km to the northwest of Tuokexun County, Xinjiang, and the stratum trend is nearly east-west. The mine field is 2.09km long from east to west, 1.36km wide from north to south, with an area of about 2.85 km$^2$. There are 7 layers of mineable coal seams in the whole area, among which the thickness of 3-3c coal seam is 1.22~8.5m, with an average of 3.83m, the dip angle is 67 °, the uniaxial compressive strength is 30 MPa, and the Protodyakonov coefficient is about 3. It belongs to the medium hard coal seam. The roof is dominated by siltstone, and the compressive strength under saturation is 4.27MPa, the softening coefficient is 0.097. It is an extremely soft rock that is easy to soften. The floor is mainly siltstone, fine sandstone and medium sandstone. Under saturation state, the compressive strength is 16.70MPa and the softening coefficient is 0.24. It is a soft rock that is easy to soften.

The mine adopts single horizontal inclined shaft development mode (Fig.1). The portal elevation of main inclined shaft is +942m and inclination angle is 16°. It is responsible for the coal and personnel promotion of the whole mine, and also serves as an intake air shaft and a safety outlet. The auxiliary inclined shaft is arranged along the 3-3b coal seam with the portal elevation of +942m and the inclination angle of 18°. It is responsible for the lifting of equipment, materials and gangue of the whole mine, and also serves as an air inlet shaft and a safety exit. The portal elevation of inclined ventilation shaft is +945.4m and inclination angle is 18°. It is responsible for the whole mine air return task, and safety exit.
The main inclined shaft, the auxiliary inclined shaft and the inclined ventilation shaft are responsible for the coal transportation, auxiliary lifting and ventilation in the mining area respectively. The mining area adopts the joint layout mining, in each section of the mining area transport, return air level from the auxiliary inclined shaft layout of the dump station and cross-cut to expose each coal seam.

3. Method of horizontal section short wall fully-mechanized caving mining

3.1. Working face roadway layout

A mine 3-3c coal seam adopts horizontal section short wall fully-mechanized caving mining method. It is the first time to appear at home and abroad, and its mining technology, support form, ventilation route and other aspects are different from the existing coal mining methods, the existing coal mining method roadway layout is no longer applicable, it is necessary to redesign the roadway layout of the working face.

The coal seam is divided into horizons with a certain elevation, and the horizon is divided into sections with a certain elevation. The mining roadway is arranged along the seam floor with a width of 4.8m and a height of 2.6m. The mining roadway is connected with the horizon haulage cross-cut through the chute and pedestrian intake air inclined roadway, and is respectively connected with the main inclined shaft and the auxiliary inclined shaft to form the coal transport system and the intake air system. The mining roadway excavation to section boundary layout mining face, through the return air inclined roadway connected to the horizon return air cross-cut, and the inclined ventilation shaft is connected to form the return air system (Fig.2). The coal pillar and top coal at the side of the roadway are recovered at the working face. bolt+I-steel+ lightweight magnesite concrete slab is used at the side of the goaf roof to construct the gob-side entry, it is formed with the height of the roadway 2.0m and the bottom width 2.0m, forming Z type ventilation at the working face (Figure 3).

![Figure 2 Layout of roadways](image1)

![Figure 3 Plan graph of roadway layout and equipment arrangement of the working face](image2)
3.2. Mining Technology

A single mining roadway is used to form a working face, to realize the integration of mining and excavation. The coal pillar and top coal beside the roadway are recovered by retreating mining, and the roadway is formed along the goaf roof side to form Z type ventilation. Main working procedure and flow chart of working face production:

1. The coal roadway fully mechanized excavator equipped with transfer machine and telescopic belt conveyor is used to drop coal, and the coal is transported out by the transfer machine and the belt conveyor successively through the chute, the horizon haulage cross-cut and the main inclined shaft.

2. Two ZZ4800/17/35H type chock hydraulic traction supports are arranged along the advancing direction, two ZF3800/17/32 type hydraulic coal caving supports are arranged horizontally perpendicular to the two traction supports. The coal draw-point is located in the side of the coal seam floor, the hydraulic support to eliminate forepole, shorten the length of canopy, at the same time, two support base is connected, a scraper conveyor is arranged below the coal draw-point, the head of the machine through the transfer machine and the belt conveyor tail lap.

3. The mining roadway along the floor layout, when the coal seam thickness is large, the roof side to form the pillar, and advance the spiral drilling recycle side pillar. The hydraulic prop is used to advance support, at the same time in advance support area to deep hole presplitting blasting of top-coal to improve the top coal caving property.

4. After pulling a step distance, the transfer machine pulls two traction supports in turn, and then takes the traction support as the support to pull two coal caving supports forward at the same time to complete the pull-off of one step distance.

5. Along the roof side of coal seam, bolt+1-steel+ lightweight magnesite concrete slab is adopted after the coal caving support to form the gob-side return air roadway.

6. First open the coal caving mechanism of support, close it after releasing 1/3 coal, then open the coal caving mechanism of the second support, also close it after releasing 1/3 coal, so alternately repeated. When gangue accounts for half of coal, stop coal caving. The released top coal is transported from the scraper conveyor to the belt conveyor through the transfer machine.

3.3. Determination of main parameters

3.3.1. Determination of section height.

The selection of sublevel height has a direct influence on the top coal caving ratio of the horizontal section short wall fully-mechanized caving face in steeply inclined coal seam. Broken degree of top coal in working face is mainly affected by the abutment pressure formed after the excavation of the mining roadway and the abutment pressure at the edge of the upper sublevel gob. Therefore, the theoretical length of sublevel top coal is the sum of the widths of the two abutment pressure zones. After the excavation of the mining roadway, the state of the primary rock stress is broken, and the stress of surrounding rock around the roadway is redistributed. The stress of top coal is shown in Fig.4.

![Stress analysis of top coal](image)
The height of limit equilibrium zone of top coal $x_1$ and the width of limit equilibrium zone in upper sublevel gob edge $x_2$ are respectively [20].

\[
x_1 = \frac{MA}{2\tan \phi_0} \ln \frac{ky_0 \cos \alpha + 2c_0 - M \gamma_0 \sin \alpha}{2\tan \phi_0} \frac{1}{\frac{2c_0 - M \gamma_0 \sin \alpha}{P_i} - \frac{A}{M}}
\]

\[
x_2 = \frac{MA}{2\epsilon \tan \phi_0} \ln \frac{kh_0 + c \cot \phi}{\epsilon (P_1 + c \cot \phi) - \frac{A}{M}}
\]

Where $M$ is the thickness of coal seam (m), $A$ is the pressure measurement coefficient, $\alpha$ is coal seam dip angle (°), $H$ is mining depth (m), $\phi_0$ is the internal friction angle of coal seam interface (°), $c_0$ is the cohesion of coal seam interface (MPa), $k$ and $k'$ are stress concentration factor, $\gamma$ is the average bulk density of overburden (kN/m$^3$), $\gamma_0$ is the bulk density of coal seam (kN/m$^3$), $P_1$ is support resistance (kPa), $P_i$ is the support resistance of the mining roadway in upper sublevel (kPa), $f$ is the friction coefficient of the contact surface between coal seam and roof and floor, $\epsilon$ is the triaxial pressure coefficient, $c$ is the cohesive force (MPa).

When the whole top coal is in limiting equilibrium, the distance between the two stress peaks is 2 times of the thickness of the coal seam. The maximum height $L$ of top coal in stress limit equilibrium state is:

\[
L = x_1 + 2M + x_2
\]

The average thickness of top coal is 3.58m, and $x_1$ and $x_2$ are 4.49m and 8.78m respectively, so the maximum sectional height is 20m. FLAC3D finite difference numerical simulation software is used to analyze the caving characteristics of top coal under the conditions of 10m, 15m and 20m respectively. The simulation results are shown in Fig.5. When the sublevel height is 10m, most of the coal in the sublevel is in the state of shear or tensile failure, and the top coal is in the state of stress limit equilibrium. When the height of the section is 15m, plastic failure occurs to the top coal around 4m above the roof, while the coal seam with a thickness of 5m in the middle of the top coal is relatively complete without plastic failure, which has a great influence on the caving property of the top coal. When the height of the stage reaches 20m, only 3m top coal above the roof is damaged. The smaller the stage height is, the larger the amount of tunneling works is and the higher the cost is. Increasing the mining and caving ratio can significantly reduce the mine production cost. Therefore, in order to ensure the free or loose space of top coal with conditions, the sublevel height is 10m, and the horizontal section height that meets the requirement of adopting low position top coal caving support should be less than or equal to 11.2~19.5m.

Figure 5 Plastic failure of top coal at different sectional heights.
(a)Section height is 10m. (b)Section height is 15m. (c)Section height is 20m
3.3.2. **Determine the mining and caving ratio.**
The coal output of the working face is composed of mining and coal caving. With the increase of mining height, the cross-section of the mining roadway increases, the amount of excavation engineering and the difficulty of support increase, and the production cost increases. Therefore, the determination of reasonable mining and caving ratio is an important prerequisite to achieve high yield and high efficiency in top coal mining. According to the statistical analysis of domestic steeply inclined horizontal sublevel fully-mechanized caving face, the reasonable mining height should be about 2.5m. As per the working face ventilation requirements, mining height \( H_g \geq \frac{Q_f}{(B_z \cdot V_{f_{max}} \cdot \phi)} \), the caving working face maximum wind speed \( V_{f_{max}} \) should be controlled below 2.5 ~ 3.0m/s, working for air \( Q_f \) is 21m\(^3\)/s, hydraulic support minimum length \( B_z \) is 4.5m, a wind profile coefficient \( \phi \) is generally 0.5~0.7, after considering the hydraulic support top-coal caving has certain space of air leakage, design take 0.6 estimate. Then the cutting height of working face should be 2.6 ~ 3.1m. After comprehensive consideration, the mining roadway height was determined to be 2.6m, the coal caving height to be 7.4m, and the mining and caving ratio to be 1:2.85.

4. **Physical similarity simulation experiment of horizontal section short wall fully-mechanized caving mining method**

4.1. **Model paving scheme**
According to the production technical conditions and the physico-mechanical properties of coal strata in a coal mine, employ variable angle plane physical simulation experiment platform (overall size is 2150×200×1800mm). As per the similarity theory, a physical similarity model with a geometric similarity ratio of 1:100 was made by taking river sand and coal ash as aggregate, gypsum and white powder (calcium carbonate) as binder, and 8-20 mesh mica powder as stratified material. The 3-3c coal seam in the model is excavated by the horizontal section short wall fully-mechanized caving mining method. Coal seam divided into seven sections from top to bottom, and the height of the sections is 10m. The specific mining layout is shown in Fig.6.

![Figure 6](image)

**Figure 6** Mining scheme of physical similarity model

4.2. **Deformation and failure evolution process of surrounding rock**
After the first sublevel mining, fracture and caving in the middle and lower part of immediate roof, and caving height was 1.2cm. The lower end of the rock beam at the fracture position is the center, and the clockwise rotation sliding occurs, while the upper end of the rock beam at the fracture position is the center, and the anticlockwise rotation sliding occurs, and the fracture development height is 2cm. The caving blocks have impact disturbance on the middle and lower areas of floor, and the development
depth of floor crack is 0.7cm (Fig. 7a). After the second sublevel mining, the roof migration characteristics of the second sublevel mining are similar to that of the first sublevel mining. Due to the disturbance of the second sublevel mining, the crack in the roof of the first sublevel further extends longitudinally to a height of 6.1cm, while the crack extends laterally but does not penetrate the second sublevel roof (Figure 7b). After the third sublevel mining, the immediate roof caving of the third sublevel caving is 1.2cm. Under the influence of three-sublevel mining disturbance, the roof caving for the second time. The caving height of the first and second subsection roof is 6.1cm and 4cm respectively. The lateral and longitudinal extension heights of the cracks in the first and second subsection roof reach 12.2cm and 6.2cm respectively. The first and second sublevel floor appear slip and failure (Fig. 7c).

![Figure 7](image)

**Figure 7** Failure evolution characteristics of surrounding rock in first to third section mining. (a)First section mining (b)Second section mining (c)Third section mining

After the fourth sublevel mining, affected by mining disturbance, the coal pillars in the first and second sublevel are unstable, the first, second and third sublevel are connected, and the roof caving for the third time. The roof caving heights of the first and second sublevel are 6.3cm and 4.0cm respectively (Figure 8a). After the mining of the fifth sublevel, the coal pillar of the third sublevel becomes instable, and the roof caving occurs for the fourth time. The caving height of the first sublevel is 8.1m, and the longitudinal development height of the crack reaches 15.6cm. No further caving occurs in the second, third and fourth sublevel due to the filling support of caving gangue, but the crack further develops in the longitudinally and lateral direction (Figure 8b). After the mining of the sixth sublevel, the coal pillar of the fourth sublevel is instable, the fifth sublevel is connected with the upper goaf, and the roof caving occurs for the fifth time. The caving height of the first, second and third sublevel is 10.8cm and the crack height is 20.6cm; the roof caving height of the fourth sublevel is 6.1cm and the crack height is 15.6cm; the crack of the fifth sublevel further extends longitudinally and lateral (Fig. 8c). After the mining of the seventh sublevel, the sixth roof caving occurs, with caving height reaching 21.7cm and fracture development height 33.1cm (Fig. 8d). The upper caving angle is 47° and the lower caving angle is 33°.

![Figure 8](image)

**Figure 8** Failure evolution characteristics of surrounding rock in fourth to seventh section mining. (a) Fourth section mining. (b)Fifth section mining. (c)Sixth section mining. (d) Seventh section mining
5. Discussion

5.1. Generalization characteristics of surrounding rock bearing structure in stope

5.1.1. Migration and transformation of roof structure
As can be seen from Fig. 9, the maximum roof caving height increases from 1.2 cm to 6.1 cm during the first to third sublevel mining, with a slow growth rate. The impact of caving gangue on floor is small, the coal pillar between section does not damage, the maximum crack height increases from 2 cm to 12.2 cm, the stress arch height is low, the failure of surrounding rock is gentle, and the roof is relatively stable. From fourth section to seventh section, maximum caving roof height from 6.3 cm to 21.7 cm, increase curve slope caving height, segmental instability of coal pillar, the large-scale caving roof, and roof-coal pillar system damage, each section fracture gradually, maximum crack height to 33.1 cm, stress arch height increase, overburden damage area, along the inclined roof structure migration cross-layer multi-ladder voussoir structure, the structural instability caused by large area roof caving, the impact on the formation of stope, further affect the stability of section coal pillar and floor.

![Figure 9](image)

By the damage evolution characteristics of surrounding rock can be seen in the process of mining, horizontal section full-mechanized caving mining in steeply inclined coal seam, roof, coal pillar and floor correlation, instability of coal pillar led to a wide range of roof caving. When from first to third sublevel mining, damage of surrounding rock is relatively moderate, after fourth sublevel stopping, roof-coal–floor chain instability occurs, will easily cause disasters. Therefore, a horizon consists of three sections with a height of 30 ~ 45 m.

5.1.2. Failure and slip mode of floor
Floor failure and slip is a kind of surrounding rock failure disaster phenomenon in steeply inclined coal seam mining, which develops with time and space. There are many main factors causing floor failure, and the mining stress environment is the main one. Research shows that stress environment in the underground coal seam is in the primary rock stress field of several orders of magnitude higher than the ground gravity stress. The mining of steeply inclined section coal seams causes the floor heave to unload to the goaf under the primary rock stress environment, when heaving a peak after selective produce structure damage and form different shapes of the sliding object, in a state of relative balance, influenced by mining disturbance, the relative balance destruction with sliding space, there will be three kinds of failure and slip modes of floor stratum, namely, extruding-translation, extruding-underdraught and extruding-upthrust. As shown in Figure 10.
5.1.2.1. Extruding-translation mode
In the initial stage of section mining, the stress field of the floor changes, forming a secondary
distribution of stress, which leads to the increase or decrease of stress in the local area, and the pressure
relief zone is formed in a certain range of the floor. The floor near the seam changes from a three-
dimensional primary rock stress state to a biaxial stress state, and the floor appears unloading and heave
deformation. As the floor heave deformation reaches the peak value, the floor selects the weak structural
surface and destroys it to form the structural object. With the movement floor, structural surface and
structural object evolution into sliding surface and sliding object, when the sliding object is balanced by
the upper and lower thrust along the inclined plane, and there is slip space, extruding-translation failure
and instability will occur. Generally, it occurs in the middle of sublevel floor and sublevel mining is not
affected by the caving of adjacent sublevel gob.

5.1.2.2. Extruding-underdraught mode
When the downward thrust of the sliding object is greater than the upward thrust along the inclined
plane, it moves downward and rotates toward the gob with the hinge point of the substructure as the
fulcrum, forming extruding-underdraught instability. When the sliding object moves under the constraint
of the roof caving block, a secondary equilibrium is formed. Generally occurs in the upper area of the
sublevel, and the sublevel is subjected to the caving impact of the upper sublevel gob.

5.1.2.3. Extruding-upthrust mode
When the downward thrust of the sliding body along the inclined plane is less than the upward thrust,
the sliding body moves upward and rotates toward the gob with the hinge point of the superstructure as
the fulcrum, forming extruding-upthrust instability. When the sliding object moves under the constraint
of the roof caving block, a secondary equilibrium is formed. It generally occurs in the lower region of
the segment and is affected by the impact of roof caving in the segment.

Figure 10  Failure and slip modes of floor. (a) Extruding-translation mode. (b) Extruding-underdraught mode. (c) Extruding-upthrust mode.
5.2. Chain instability of surrounding rock bearing structure

In steeply inclined coal seam mining process, the cross-layer multi-ladder voussoir structure is formed by transformation and migration of the critical layer, the floor damage slip along the potential sliding surface, section coal pillar is affected by the clamping effect of roof and floor to form partial or whole failure, and there is spatial-temporal correlation between broken coal pillar and falling gangue, roof and floor, which forms the bearing structure of the surrounding rock of the stope as a whole. Relative to the flat seam or gently inclined seam mining, the stability of stope surrounding rock bearing structure is mainly controlled by key stratum. The bearing structure elements of the surrounding rock in steeply inclined coal seam mining are varied, which are mainly composed of cross-layer multi-ladder voussoir structure of roof, floor failure and slip, and section coal pillar. The roof structure and the failure and slip of floor is widely distributed along the tendency, and the key rock blocks that control it are located in variable rock strata, forming the generalization characteristics of the surrounding rock bearing structure of this kind of coal seam, as shown in Fig.11. Roof, pillar and floor of the bearing structure are interrelated through stress and load transfer, forming a Roof-Pillar-Floor (R-P-F) chain structure. When the first sublevel mining, the roof (R₁) and floor (F₁) form a chain structure through the stress transfer between section coal pillars (P₁, P₂). When multi-sublevels are mining, the roof (R₁, R₂…Rₙ) and floor (F₁, F₂…Fₙ) form a strong or weak chain structure through the stress transfer between section pillars (P₁, P₃ …Pₙ₊₁). The stability of R-P-F chain structure is a nonlinear dynamics problem, the chain structure interact with external mining environment, the internal structure through the strong or weak chain connected between the units, a strong chain control space large instability of surrounding rock, weak chain control the local failure of the surrounding rock. In the process of mining, the strong and weak chains between structural units convert each other, forming a dynamic process of disaster inoculation, development and evolution of surrounding rock in steeply inclined coal seam mining.

In the process of 3-3c coal seam horizontal section short wall fully-mechanized caving in a coal mine, when the first to third sublevel are mining, the section coal pillar has no overall instability, the roof hanging area is not large, the floor failure and slip area is small, the R-P-F chain structure is complete, and the stope surrounding rock is stable. When the fourth to seventh sublevel is mining, these sublevel R-P-F chain structure is stable, but the upper section coal pillar is unstable as a whole, and the structural chains of R₁,₂,₃-P₁,₂,₃ are fractured. The roof caving extends the longitudinal height, and the transverse fractures are connected. The roof caving causes impact on the section coal pillar, enlarges the floor failure and slip area, and intensifies the failure of the surrounding rock of the stope.

6. Conclusion

(1) In order to break the fully mechanized mining technical forbidden area of steeply inclined coal seam with thickness of 4~8m, innovatively proposed a horizontal section short wall fully-mechanized caving mining method. Through the single roadway integrated with mining and excavation is arranged as working face, the pillar on sides of roadway is recovered by spiral drilling, and the top coal is recovered
by the vertical and horizontal self-moving supports. The bolt+I-steel+ lightweight magnesite concrete slab is used to support gob-side entry, and the Z type ventilation mode is formed in the working face. These techniques effectively solved the difficult problem of safe and efficient production of the coal seam.

(2) The reasonable height of section is 10m, height of the mining roadway is 2.6m, caving height is 7.4 m, and it is better to cave the top coal. In the sublevel mining process, the failure of surrounding rock is relatively moderate in the first to third sublevel mining, the overall instability of section coal pillar does not occur, and there is no connection between sublevel mining. After the fourth sublevel stopping, the whole instability of sublevel coal pillar occurs, leading to the chain instability of Roof-Pillar–Floor structure, and the roof caving in a large area, which is easy to cause impact disaster. Therefore, a horizon consists of three sections with a height of 30~ 5 m

(3) The cross-layer multi-ladder voussoir structure is formed by transformation and migration of the critical layer, the failure and slip modes of floor along the potential sliding surface are extruding-translation, extruding-underdraught and extruding-upthrust in different areas and coal pillar is affected by the clamping effect of roof and floor to form partial or whole failure of horizontal sublevel short wall caving stope in steeply inclined thick coal seam. Roof, pillar and floor are interrelated, forming the chain structure of Roof- Pillar -Floor in stope. The structure has the generalization characteristics, showing various components, wide distribution range and variable control positions. The strong and weak chains of the chain bearing structure units are converted to each other in the process of mining, forming a dynamic process of surrounding rock disaster breeding, development and evolution.

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