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Spatial structure evolution of overlying strata and inducing mechanism of rockburst in coal mine

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Abstract: Spatial structure of overlying strata existed and evolved dynamically with the exploitation scope (boundary conditions) changes in coal mines and to induce rockburst. Based on the "key strata" theory, the integrated spatial structure of overlying strata was put forward, which was composed of "O−X" structure in the plane section and "F" structure in the vertical section. The formation and ongoing instability of the "O−X" and "F" structures were called as dynamic evolution cycle of the overlying strata. Three basic categories of "O−X", "F" and "T" structures were defined, and the strata behaviors of each spatial structure were analyzed. According to energy theory, mechanism of rockburst induced by spatial structure instability was discussed. The research expanded the scope of traditional ground pressure theory and provided a guide for the prevention of rockburst and mining tremors induced by structure instability of overlying strata.

Key words: spatial structure; overlying strata; rockburst; key strata

1 Introduction

With the increase of mining depth and intensity, dynamic disasters have become gradually serious, of which rockburst and mining-induced tremor are the main forms [1−4]. According to the energy theory, the occurrence of rockburst satisfies "superposition principle of static-dynamic loads" [5−7], namely, the dynamic disaster will happen when the superposition of static load in coal measure strata around mining space and the dynamic load generated by mining-induced seismicity exceed the minimum load. Especially, overlying strata damage and movement is one of the main reasons to generate dynamic load [8−10].

The overlying strata will fracture and move as the result of coal seam exploitation, and both static and dynamic load will be applied to the roadways and workfaces in this process, inducing roof and rockburst disasters [11]. Overlying strata movement is not only the result of a single workface, but also the interaction of more faces. Microseismic monitoring results show that the rockburst sources are mainly concentrated in the adjacent gobs especially when thick and hard key strata exist, which indicates that spatial structure of overlying strata exists in the coal mine and can evolve dynamically with the exploitation scope (boundary conditions) changes [12].

In the past, numerous researches have been carried out to investigate the instability of strata structure as well as coal or rock dynamic failure mechanism, and great achievements have been obtained [13−16]. The most important outcomes are the "Voussoir Beam" and "Key strata" theories of roof strata proposed by QIAN et al [17,18], which provide the theoretical basis for studying the formation and instability of overlying strata [17,18]. JIANG et al [19] proposed the concept of spatial structure of overlying strata, and made four categories

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(θ, O, S, and C types) based on the boundary conditions of the workface. The excellent jobs have important guiding significance for expanding the scope of traditional underground pressure. But it was found that most the previous studies were confined to limited zones not far from the coal seam, which in the vertical direction were not more than the main roof and in horizontal layer within the scope of abutment pressure. Nevertheless, dynamic disasters such as rock bursts and mining-induced tremors have involved range to the main key strata and were more than mining influencing zones. On the basis of analyzing mining tremors and rockbursts rules during the first "square" of one workface, second "square" of two workfaces and third "square" of three workfaces, the spatial structure evolution of overlying strata was studied based on the key strata theory in this work. The structure and fracture characteristics both on the horizontal and vertical layer of the overburden strata were discussed, as well as the effect to rockburst during the evolution of spatial structure. The research achievements would provide a guide to reveal the mechanism and prevention of rockburst induced by instability of overlying strata structure.

2 "Square effect" of overlaying strata and rockburst phenomenon

The movement height of roof strata in the goaf is controlled by its short side which is generally the workface width. The roof movement height and strength will reach the maximum when the mining distance rises to the workface width, and will not rise with the coal mining advance if the workface is not wide enough. The roof movement will develop to upper strata until the next workface is exploited since the gob width enlarges, the roof activities strengthen gradually and reach the maximum again when the mining distance equals to about the width of two gobs, therefore, roof movement will gradually strengthen with the increase of gob size before it develops to the surface. The phenomenon is called as "square effect" by rockburst experts.

The "square effect" exists in many collieries, for instance, a longwall workface located at 34 mining district, No.3 mining level of a coal mine in China, is 182 m in width and 690 m in length, so far 375 m has been extracted and 315 m is left with fully mechanized coal winning technology. The coal seam is 3.38 m in thickness on average with the dip angle of 28° to 31°. The immediate roof is gray siltstone with the thickness of 5.9 to 15.6 m, the main roof is gray gritstone, 44.9 to 69 m in thickness, and the floor is the off-white fine siltstone of 1.3 to 22 m in thickness. The pillar between the tailentry and the goaf is 2 to 8 m in width.

Two gobs adjacent to the tailentry side of the workface are shown in Fig. 1. A strong tremor with the energy of 1×10^6 J occurs when the workface advances to the first square area. And when the workface advances to the second square area, tremors with energy of 10^4 J and 10^5 J increase. At the third square, the seismicities are concentrated toward to the tailentry and those with energy of exceeding 10^4 J increase significantly, which indicates that the coal/rock failed is aggravated and the energy release is enhanced, followed by several tremors energy larger than 10^5 J. Finally, a strong rockburst disaster occurs. As shown in Fig. 1, high energy mining tremors happen densely at all the three square areas.

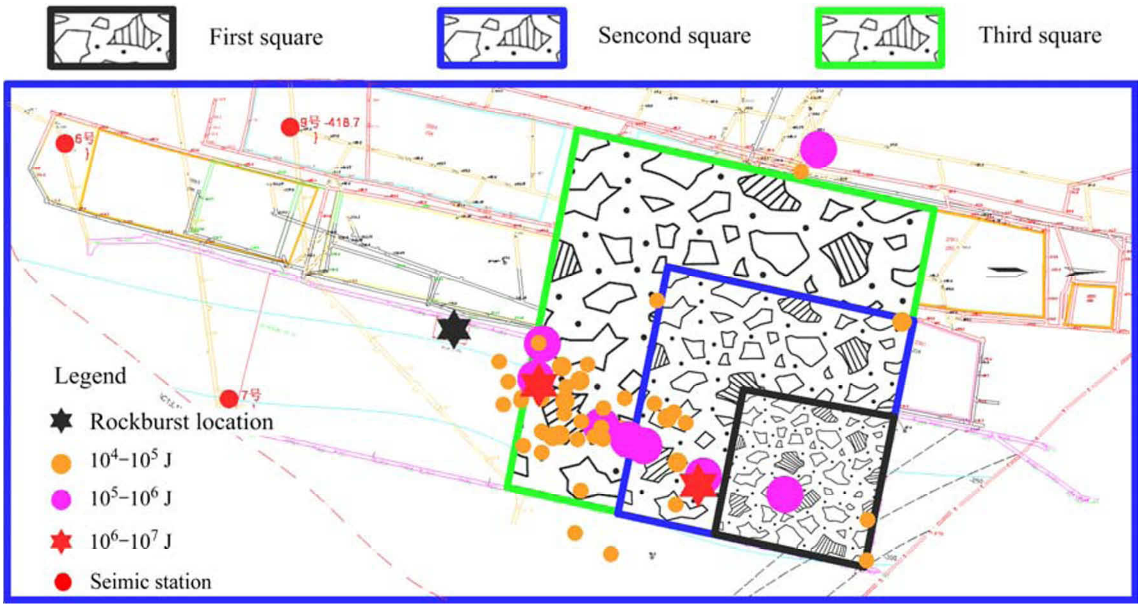

Fig. 1 Relationship between "square effect" of overlying strata and strong mining tremors

3 Evolution of spatial structure of overlying strata

3.1 “O−X” structure of roof movement

The morphology of each key strata forms an “O−X” structure after being fractured in the plane section, the “O−X” structures at different layers will form a column-platform-rotating surface body, the adjacent boundary key strata is denoted as “F” structure in the vertical section. The “O−X” structure in the plane section will develop up to the ground, at the same time, the “F” structure also destabilizes with the upward development of strata movement. So “O−X” and “F” structures and their mutual conversion together constitute the integrated spatial structure of overlying strata, the formation and instability of the “O−X” and “F” structures ongoing continually is called dynamic evolution cycle of the overlying strata in coal mine.

QIAN [17,18] pointed out the main roof formed “O−X” breaking after the coal exploitation. Similarly, the overlying strata in wide range also formed “O−X” structure, on the profile along the advance and strike direction of the workface, the fractured roof articulated with each other and obtained balance as “Voussoir Beam”, as shown in Fig. 2. The morphology and scope of the “O−X” structure are determined by the workface length, coal thickness, key strata position as well as the mechanical properties.

The “O−X” spatial structure can be classified into two categories based on the breaking of the key strata or not: 1) global spatial “O−X” structure when the main key strata fractures and 2) semi-spatial “O−X” as the main or sub key strata maintains integrate. Since the boundaries around the “O−X” spatial structure workface are solid coal seam, the strata behaviors during coal extraction are mainly affected by stress field changes and dynamic loads caused by the formation and instability of “Voussoir Beam” of each key strata. Sometimes when thick hard roof exists, the dynamic disturbance during roof weighting is much more serious because of large weighting step. And if several sub key strata over the coal seam that satisfy the compound breakage, the strata behavior will be much stronger.

The “O−X” structure caused by the key strata is the basic form of spatial structure evolution in coal mine, as well as the boundary and important part of other spatial structures.

3.2 “F” structure of workface with one side adjacent to gob

The workface, which one side adjacent to the gob with small pillar between them and the other side is solid coal or big pillar, is defined as “F” spatial structure of overlying strata, because the strata adjacent to the gob formed by the “O−X” structure looks like the letter “F”. “F” structure workface is significantly influenced by the reactivating and caving of “O−X” structure in the gob. So, overlying strata movement of the “F” structure includes two parts, the cooperative motion with part of strata in the gob and its own “O−X” structure evolution. Similar to “O−X” spatial structure, the “F” structure model can be classified into two categories, long and short arm “F” structures corresponding to the subcritical extraction and full subsidence of the gob, respectively. Both the long and short arm “F” structures include single and multi-“F” depending on the number of key strata above the seam. Figures 3(a) and (b) show the long-arm “F” structure that one key stratum, usually the main key stratum maintains intact as the width of the gob is too short to exceed the limit span. If the total width of the gob and workface exceeds the limit span, the main key stratum will rupture and form a big “O−X” structure. Figures 3(c) and (d) show the short-arm “F” structure, in this situation the width of the gob is large enough and all the key strata fractured, the subsidence of the surface reaches the maximum. The difference between the long-arm and short-arm is that whether the main key strata ruptures and this will result in different stress field and strata behaviors. Since the “F” structure contains two types of strata movement, namely, the “O−X” rupture and instability of the “F” arms in the gob side, the strata

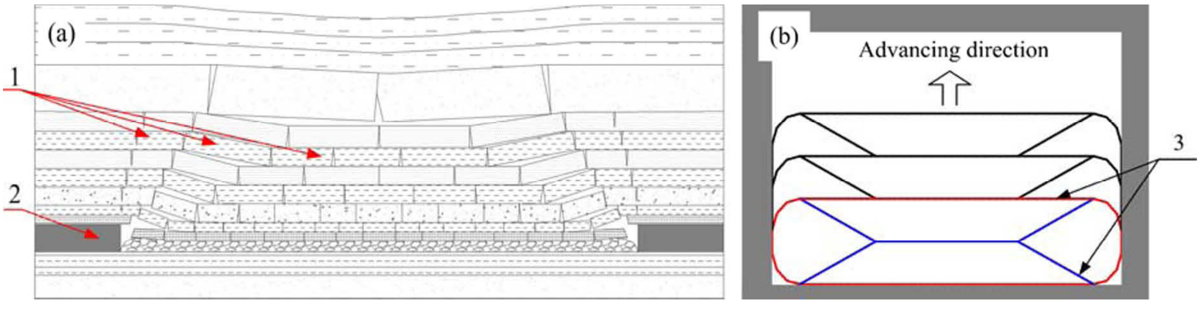

Fig. 2 “O−X” spatial structure of overlying strata: (a) “Voussoir beam” structure of advancing direction profile; (b) “O−X” structure of strata of layer planar (1—“Voussoir beam” structure; 2—Solid coal seam; 3—O−X-fracture line)

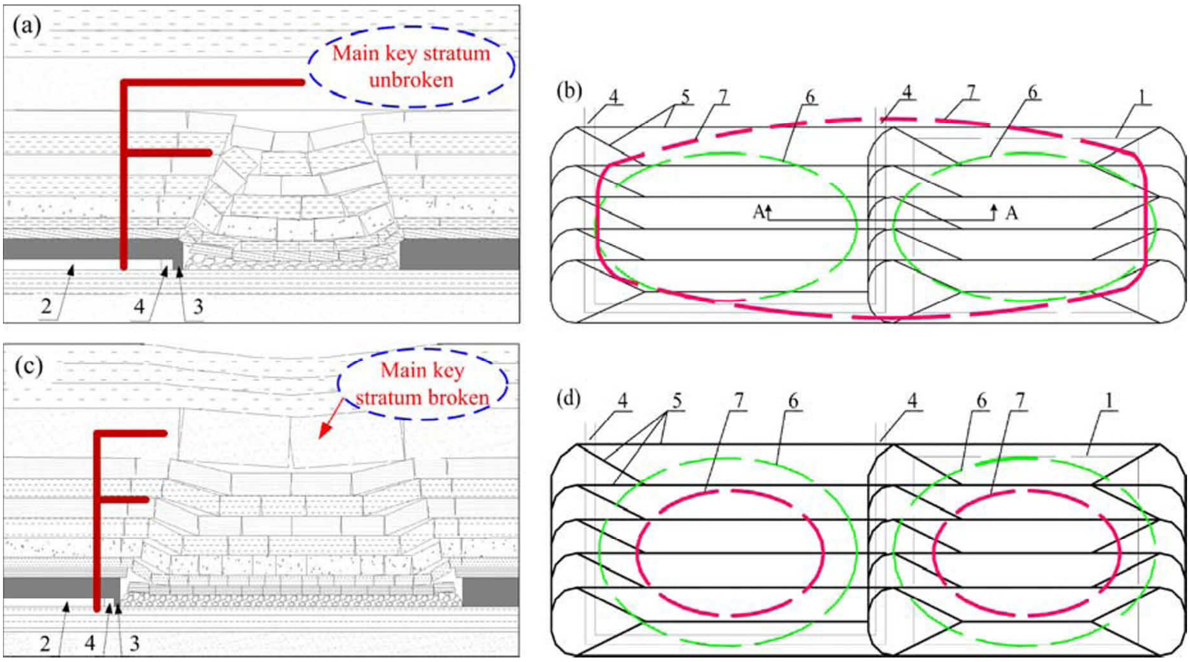

Fig. 3 Schematic diagram of "F" spatial structure and classification of overlying strata: (a) Profile of long-arm "F" structure of overlying strata; (b) Plan of long-arm "F" structure of overlying strata; (c) Profile of short-arm "F" structure of overlying strata; (d) Plan of short-arm "F" structure of overlying strata (1—Gob of previous district sublevel; 2—Next workface adjacent to the gob; 3—Small pillar between two workfaces; 4—Entry of the next workface; 5—Fracture line of the main roof; 6—Fracture line of higher key strata; 7—Fracture line of main key strata)

behaviors are much more complex than those in single workface. The characteristic of "F" structure is that the strata arm (short or long) will coordinately move under mining activities, therefore, rockbursts are induced in the gob and the gob-side entry.

3.3 "T" structure of island workface

The island workface is characterized by gobs around and the coal pillars less than the needed minimum width that separate the connection. The strata behavior is much stronger than non-island workface because of the higher stress concentration and violent strata movement, easily leading to rockburst or other dynamic disasters [20]. The abutment stress of the island workface is characterized by high peak, distant disturbance and rapid change because overlying strata around the island workface have already fractured and parts of them will move collaboratively with that above the workface. The overlying strata on both sides of the island workface are "F" structures, overall look like the letter "T", so named as "T" spatial structure. The "T" structure can be divided into three categories based on the state of key strata, that is, 1) symmetrical short-arm "T" corresponding to that the main key strata have been already broken; 2) symmetrical long-arm "T" corresponding to the that the main key strata of both side gobs still keep integrated, 3) asymmetric "T" structure that the main key strata fracture in one side gob and the other side maintain integrated. Each type of "T" structure includes single and multi-"T" depending on the number of key strata above the coal seam. Figures 4 (a)−(f) demonstrate the planar and profile graph of short-arm "T", long-arm "T" and asymmetric "T" structure, respectively. Each "T" structure displays different strata behavior because of different strata movement mode. Strata behavior in the whole workface of the first category structure is similar to the gob side of the short-arm "F". However, in long-arm "T" structure side, abutment pressure is higher than that of short-arm "T" since the key strata maintain integrated, resulting in difficulty of roadway maintenance and numerous seismic activities. After the workface advances forward to a considerable distance, the key strata will undergo the first and periodic weightings, thereby causing high energy tremors. Although these tremors locate in both sides of the gobs and middle of the workface can also induce rockburst accidents because of the strong seismic energy. With regard to the third type "T" structure, the abutment pressure is similar to the first type at the long-arm side and similar to the second type at the short-arm side before the first weighting of the long-arm strata. But the strata behavior will be much more violent than that of the first two categories after the fracture and movement of the long-arm key strata, the main reason is that the fracture lines of long-arm strata locate at the top of the roadway, and the destruction caused by the dynamic

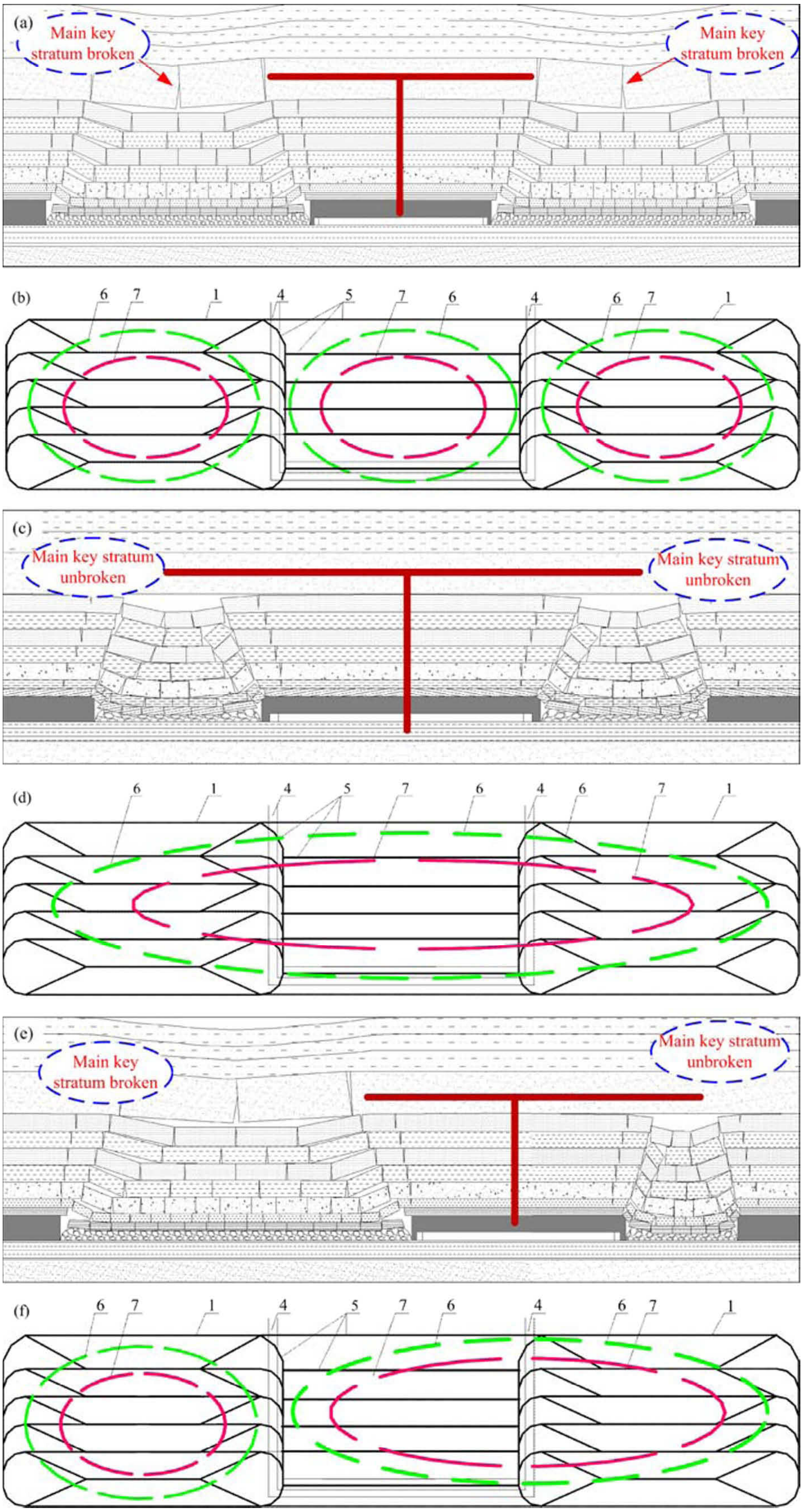

Fig. 4 Sketches and classification of “T” overlying strata spatial structure: (a) Profile of symmetrical short-arm “T” structure of overlying strata; (b) Plan of symmetrical short-arm “T” structure of overlying strata; (c) Profile of symmetrical long-arm “T” structure of overlying strata; (d) Plan of symmetrical long-arm “T” structure of overlying strata; (e) Profile of asymmetrical “T” structure of overlying strata; (f) Plan of asymmetrical “T” structure of overlying strata

impact of the tremor wave is much more severe.

4 Discussion on rockburst mechanism induced by spatial structure evolution of overlying strata

4.1 Mining-induced tremor during formation of “O−X” structure

The key strata start to break, cave and finally form “O−X” structure with the hanging area increasing gradually as coal exploitation. During this process, a mass of elastic energy accumulated in the roof strata releases suddenly and leads to strong tremors that probably cause rockburst disaster. Researches show that bending elastic energy accumulated in the roof before the first weighting can be obtained as follows:

$$U_{\mathrm{W}}=\frac{q^2L^5}{576EJ} \tag{1}$$

where L is the roof length; q is the load on the roof; E is flexural rigidity; J is the moment of inertia. The bending elastic energy is proportional to the 5th power of the roof length.

For example, assuming that the workface is 150 m in length, q is 5×10^5 N/m^3, EJ equals to 4×10^{11} N·m^2, so when the roof strata reaches square, that is “square effect”, the bending elastic energy of the roof before “O−X” fracture can be 7×10^7 J. When the overlying strata above two workface present the second “square effect”, the energy reaches 2.5×10^9 J, for the third “square effect” the energy is 1.8×10^{10} J, with such huge energy release is likely to induce rockburst disasters.

4.2 Effect of “F” structure

As mentioned above, one side of workface is gob and pillar can hardly separate the connection between each other, the overlying strata will form “F” structure. The “F” structure leads to not only high stress concentration but also frequent rockbursts because of cooperative movement of “F” structure arm under mining activities.

For the short-arm “F” structure, assuming that the cantilever of the “F” arm is one fifth of the workface width, that is almost 30 m cantilever of strata acting on the gob-side pillar. For long-arm “F” structure, the cantilever is nearly 75 m, while the long-arm “F” workface with two gobs the cantilever is nearly 150 m that acting on the pillar.

Similarly, the longer the cantilever, the more bending elastic energy accumulated in the roof strata, one can obtained

$$U_{\mathrm{W}}=\frac{q^2L^5}{8EJ} \tag{2}$$

4.3 Effect of “T” structure

The “F” spatial structure of overlying strata is caused by one side gob; however, “T” spatial structure is caused by two-side gobs, so the roadways of the island are suffered not only by the static and dynamic loads caused by the long or short “T” arm, but also by the large-scale movement of overlying key strata, these factors will cause the high rockburst risk of island workface.

5 Conclusions

1) Spatial structure of fractured overlying strata exists in coal mines and the dynamic evolution of spatial structure can induce rockburst disasters. Microseismic monitoring results show a close relationship between “square effect” of overlying strata and mining-induced tremors.

2) Based on the “key strata” theory, the integrated spatial structure of overlying strata is put forward that composed of “O−X” structure in the plane section and “F” structure of the vertical section. The formation and instability of the “O−X” and “F” structure ongoing continually are called dynamic evolution cycle of the overlying strata in coal mine.

3) Three basic categories of “O−X”, “F” and “T” structure workface are defined, while classifications and strata behaviors of each spatial structure are determined based on the state of key strata.

4) According to energy theory, mechanism of rockburst induced by spatial structure instability of overlying strata is discussed and the effect of “F” and “T” is analyzed. The strata behaviors and mining-induced tremors of “F” and “T” structure workface are more violent than those of “O−X” structure.

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煤矿覆岩空间结构演化及其诱冲作用

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摘　要：煤矿覆岩存在空间结构，并且随着采空范围(边界条件)的不同，覆岩的空间结构是动态演化的，并能诱发冲击矿压灾害。基于关键层理论，提出煤矿覆岩的整体空间结构形态，即层面方向的“O−X”结构与剖面方向的“F”结构组成。“O−X”结构与“F”结构的形成与失稳不断进行，称为煤矿覆岩空间结构的动态演化。将覆岩空间结构分为“O−X”型、“F”型与“T”型三种基本类型，对三类空间结构进行细化，分析其矿压特征与规律。基于能量理论，讨论覆岩空间结构演化诱冲的机制，计算三类结构“见方”时的弯曲弹性能，并分析“F”、“T”结构对诱冲的作用。研究拓展传统矿压理论范围，为覆岩结构失稳型冲击矿震预防提供理论指导。

关键词：空间结构；覆岩；冲击矿压；关键层

(Edited by Chao WANG)