Behaviors of overlying strata in extra-thick coal seams using top-coal caving method

Bin Yu
Datong Coal Mine Company, Datong, 037003, China

ABSTRACT
Accidents such as support failure and excessive deformation of roadways due to drastic changes in strata behaviors are frequently reported when mining the extra-thick coal seams Nos. 3–5 in Datong coal mine with top-coal caving method, which significantly hampers the mine’s normal production. To understand the mechanism of strata failure, this paper presented a structure evolution model with respect to strata behaviors. Then the behaviors of strata overlying the extra-thick coal seams were studied with the combined method of theoretical analysis, physical simulation, and field measurement. The results show that the key strata, which are usually thick-hard strata, play an important role in overlying movement and may influence the mining-induced strata behaviors in the working face using top-coal caving method. The structural model of far-field key strata presents a “masonry beam” type structure when “horizontal O-X” breakage type happens. The rotational motion of the block imposed radial compressive stress on the surrounding rock mass of the roadway. This can induce excessive deformation of roadway near the goaf. Besides, this paper proposed a pre-control technology for the hard roof based on fracture holes and underground roof pre-splitting. It could effectively reduce stress concentration and release the accumulated energy of the strata, when mining underground coal resources with top-coal caving method.

© 2016 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. All rights reserved.

1. Introduction

Datong mining area, a large-scale coal production base in China, is basically characterized by hard and thick roof. Over the past decades, Datong Coal Mine Group Company has made significant effort on investigation of hard roof controlling of this mining area, and significant technical and economic benefits were achieved (Yu, 2010). With the decreasing depth of the upper Jurassic coal resources, the mining operation transfers to a deeper layer of carboniferous coal seams Nos. 3–5 (with a thickness of 14–20 m). In this case, some problems appear, for example, the frequent turn-on and turn-off of the safety valves in hydraulic supports, excessive deformation of the gateway 150 m ahead of the working face, roof fall and support crushing at the working face. The aforementioned problems are the challenging issues on the safety and high-effective production of this mining area. Therefore, it is crucially important to have good knowledge of behaviors of the strata overlying extra-thick coal seam during mining when using top-coal caving method.

Over the past decade, several studies have been shown on the behaviors of the overlying strata in extra-thick coal seam. Xu and Ju (2011), Ju and Xu (2013) and Xu et al. (2014) studied the structural morphology of the key strata and its influence on strata behaviors in longwall mining of thick coal seam and pointed out that the strata behaviors may vary with strata structures. The effects of top coal caving method on hard roof, caving pace, and bending deformation effects on strata movement were also observed (Tai, 1965; Wu and Yang, 1990; Tan, 1991; Zhao et al., 1991; Singh and Singh, 1999; Unver and Yasitli, 2006; Mandal et al., 2008; Pan et al., 2012). Shi and Jiang (2004) and Liu (2005) numerically analyzed the breaking and motion characters of roof with mechanical model. Some suggestions on how to control the hard roof were proposed (Xu and Gu, 1985; Singh et al., 2001, 2008; Singh, 2004; Yang, 2013; Yu and Duan, 2014). Kong et al. (2010) studied the working resistance of support in fully-mechanized sublevel caving face in extra-thick coal seam and pointed out that the working state of support can be divided into three categories, i.e. normal roof strata pressure, low and high roof strata pressures. Huang (2013) proposed the regularities of roof strata fracture of fully-mechanized caving mining under goaf in extra-thick coal seam and stated that the longitudinal fissure is the governing factor of roof failure of extra-thick seam under goaf. Guo (2012) attributed...
2. Engineering background

The main coal seams of the study area in Datong mining area are composed of Carboniferous and Jurassic coal seams. The shallow Jurassic coal seams resources depletion is observed after years of extraction. The mining operation is gradually transferring to the deep Carboniferous coal seam. At present, Tashan and Tongxin collieries are generally exploited at the Carboniferous coal seams Nos. 3–5, with an average thickness of 15–18 m. In between the two coal seams, there exist sandstone (fine-, medium-, and course-grain), siltstone, and sandy mudstone. The sandy mudstone accounts for 90–95%, and mudstone and coal seam for 5–10%. The distance between the upper and lower coal seams is 150–280 m. The annual production of a single working face reaches 10 Mt, and the horizontal displacement of roadway is up to 1 m. Even though the resistance of support type ZF15000/27.5/42 in field reaches a value of 15,000 kN, supports crush occasionally at the working face, which poses a major threat to the safe mining operation. The deformations of the roadway and the safety valve opening of hydraulic support in field are shown in Fig. 1. The layout of the working face No. 8203 in the study area is shown in Fig. 2.

It is known that the mining-induced pressure has a close relationship with the breaking character of overlying strata. Different breaking characters of key strata in near- and far-field will have a sound effect on mining-induced pressure subsequently. The strong strata behaviors to the instability of compound key strata with respect to the surface subsidence using field measurements, and the relationship between surface subsidence and movement of key strata was also numerically analyzed. The previous studies are mostly focused on the movement regulation of strata and control measures, but few studies are reported on the “large-space, near- and far-field” key strata and the effects of key strata fracture on near- and far-field when mining extra-thick coal seam. In this context, structure evolution of overlying strata in extra-thick coal seam, as well as its effect on strata behaviors, will be focused on.

3. Key strata and behaviors of surrounding rock in near field

Using conventional top-coal caving method, the scale of roof movement in extra-thick coal seam can expand apparently and the main roof will turn into immediate roof. Generally, two kinds of structures of near field in extra-thick coal seam will form. One is a key stratum in immediate roof located in caving zone during mining process where a cantilever beam can be formed. The basic overlying roof forms a voussoir beam, namely the overlying strata produce a “cantilever beam and voussoir beam” structure. The breaking of cantilever beam tend to cause small periodic weighting while the collapse of the main roof can cause huge periodic weighting. Field monitoring results of strata behaviors reveal the space of 12–20 m for small periodic roof weighting and 21–40 m for the huge one.

The key strata near the working face tend to form the structure of cantilever beam and voussoir beam when breaking (Fig. 4). Because of the free face of the cantilever beam's end structure, the load of breaking block will transfer to the supports at the working face. When the load from voussoir beam breaks the structure of cantilever beam, the broken part will rotate under the huge pressure imposed. In this circumstance, the load that acts on the working face supports will change as a combined load applied to cantilever beam and voussoir beam in a short time. Then strong strata behavior with small roof weighting step can be formed. The huge load on the support increases sharply, resulting in the difficulty of supports.

4. Measurement of strata movement in stope

4.1. Measurement of fracture height of overlying strata

In order to investigate the failure mechanism of large-space overlying strata, top-coal caving method was adopted for the extra-thick coal seam of Carboniferous system. EH-4 magneto-telluric and intelligent drillhole optical imager equipment was adopted in the working face No. 8100 in Tongxin coal mine. The layout of monitoring points of EH-4 is shown in Fig. 5, and the images of strata failure status are illustrated in Fig. 6.

Fig. 7 shows two-dimensional (2D) rock mass resistivity monitored by the measuring line No. 2 in the first, second and third stages, respectively (double black dotted lines are the coal seam position). In the first stage, there is a high resistance closed circle in the horizontal direction, with distance of 80–300 m at elevation of +800 m to +900 m (as shown in the red dotted line in Fig. 7a), above which the resistivity contour is smooth, continuous and...
layered. Accordingly, we can consider the high resistivity anomaly as the caving zone in top-coal caving mining of the working face No. 8100 with influencing height of 100 m. The blue red dotted line represents the boundary of fractured zone after mining, with the influencing height of 170 m. The bending zone is considered from the boundary of fractured zone to surface. The form and scope of high resistivity anomaly in the second stage (Fig. 7b) are basically similar to those in the first stage (Fig. 7a). The resistivity contour is also smooth, continuous and layered in the third stage, indicating that the overlying strata become stable after one year and then are layered.

The results of borehole imager and physical detection indicate that the average mining height is 15 m in Carboniferous system. The fractured zone can reach 150–180 m, and the ratio of the fractured zone height to the mining height is 10–12 in top-coal caving mining, resulting in a large-scale stope and a large-scale strata movement.

In combination with the identification results of the key strata in the roof (Carboniferous) in Fig. 3, three key strata between the Carboniferous and Jurassic coal seams were observed within the scope of mining-induced fracture of the coal seams Nos. 3–5.

<table>
<thead>
<tr>
<th>Number</th>
<th>Thickness</th>
<th>Depth</th>
<th>Lithology</th>
<th>KS</th>
<th>Hard rock</th>
<th>Legend</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>17.1</td>
<td>323.95</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>1.35</td>
<td>325.30</td>
<td>Gritstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>3</td>
<td>328.30</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>1.95</td>
<td>330.25</td>
<td>Fine sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>9.6</td>
<td>339.85</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>2.45</td>
<td>342.30</td>
<td>Gritstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>9.85</td>
<td>352.15</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>19.35</td>
<td>371.50</td>
<td>Gritstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>23</td>
<td>394.50</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>3.55</td>
<td>398.05</td>
<td>Fine sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>18.65</td>
<td>416.70</td>
<td>Gritstone</td>
<td>KS</td>
<td>Third hardrock</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>2.24</td>
<td>418.94</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.9</td>
<td>419.84</td>
<td>Gritstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>4.71</td>
<td>424.55</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>4.61</td>
<td>429.16</td>
<td>Gritstone</td>
<td>KS2</td>
<td>Second hardrock</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0.97</td>
<td>430.13</td>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0.42</td>
<td>430.55</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0.6</td>
<td>431.15</td>
<td>Siltstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>2</td>
<td>433.15</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0.8</td>
<td>433.95</td>
<td>Siltstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0.75</td>
<td>434.70</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.9</td>
<td>435.60</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>2.4</td>
<td>438.00</td>
<td>Fine sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>439.00</td>
<td>Gritstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1.6</td>
<td>440.60</td>
<td>Fine sandstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>8.3</td>
<td>448.90</td>
<td>Gravel</td>
<td>KS1</td>
<td>First hardrock</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.1</td>
<td>452.00</td>
<td>Siltstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>2.56</td>
<td>454.56</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2.67</td>
<td>457.23</td>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.12</td>
<td>458.35</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1.14</td>
<td>459.49</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>460.09</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.38</td>
<td>460.47</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.25</td>
<td>460.72</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.98</td>
<td>461.70</td>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.16</td>
<td>463.86</td>
<td>Sandy mudstone</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>19</td>
<td>482.86</td>
<td>Coal</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Columnar section between two coal seams obtained from borehole No. 1204 and associated strata. Units of thickness and depth are in m.

Fig. 4. Structure of "voussoir and cantilever" beams.
4.2. Microseismic monitoring of overlying strata structure movement

The microseismicity monitoring results of working face No. 8103 in Tashan coal mine are shown in Fig. 8. It indicates that during the top-coal caving mining of extra-thick coal seam, the upper strata begin to fracture about 75 m ahead of the rib and the fracture height in the area of strong microseismicity is about 50 m. The average fracture height is about 75 m and the periodic rupture height is 150 m with the maximum value of 200 m in local region. The scope of advancing fracture in the working face is about 100 m and the abnormal noises can always be recorded during mining.

Based on the microseismicity monitoring results, the position of strata in vertical direction has a significant effect on the fracture developments of strata in horizontal direction. The roof and floor near the working face are the concentrated areas of strong microseismicity. The fracture gradually develops from the upper strata to the lower ones.

Fig. 5. The layout of monitoring points of EH-4.

Fig. 6. Status of roof failure.

Fig. 7. Two-dimensional (2D) inversion of strata resistivity monitored by the measuring line No. 2.
5. Structure model of far-field strata for large-scale stope

5.1. Structure model of “voussoir beam” formed by “horizontal O-X” fracturing of far-field key strata

Stratum breaking above mining working face can be divided into two types, i.e. “vertical O-X” and “horizontal O-X”, depending on the direction of stratum middle fracture line parallel or perpendicular to the advance direction. The upper roof strata fracture, in a form of plate as a consequence of large mined-out space in the extra-thick coal seams, adopts top-coal caving method. The space of the broken block movement decreases gradually with increasing distance between the roof strata and coal seam. The strata with different distances to coal seams tend to have various dimensions of hanging arches in terms of the dip and strike of working face, resulting in different rock breaking angles and thereby, leading to the variations in fracture characteristics of the strata.

By analyzing the fracture characteristics of the first key stratum (KS1) based on the thin plate theory proposed by Qian et al. (2010), the fracture criterion of KS1 can be used to other key strata of overlying layers. The suspension length in dip direction \( b \), the width of working face \( l \), and the limited span of key strata \( l_m \) (Fig. 9) can then be classified as follows:

1. When \( b > 3l_m \), the roof weighting pace yields \( a = l_m \).
2. When \( 3l_m > b > 1.414l_m \), the roof weighting pace is \( l_m < a < 1.414l_m \).
3. When \( a = b = 1.414l_m \), the square-shaped roof caving forms.
4. When \( l_m < b < 1.414l_m \), the roof weighting pace yields \( a > 1.414l_m > b \).
5. When \( b < l_m \), the roof is stable and thus will not be caved.

Combining with the data shown in Fig. 3, we take Tongxin coal mine working face No. 8203 as an example. The width is 200 m, and a single working face during mining is used. The length of each key stratum \( b \), the limit span \( l_m \), and the roof weighting pace \( a \) can be obtained as listed in Table 1.

On the basis of the classification results as discussed earlier, it is clear that interval of roof breaking of KS1 and KS2 can be classified as the main roof breakage types of near-field key strata of the first and second categories, respectively; whilst the key stratum (MKS) is far-field key layer which meets the conditions of \( l_m < b < 1.414l_m \) and \( a > 1.414l_m > b \). In this case, the key strata in a form of the

<table>
<thead>
<tr>
<th>Key stratum</th>
<th>Suspension length ( b ) (m)</th>
<th>Limit span ( l_m ) (m)</th>
<th>Roof weighting pace ( a ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KS1</td>
<td>180</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>KS2</td>
<td>160</td>
<td>92</td>
<td>92–130</td>
</tr>
<tr>
<td>MKS</td>
<td>120</td>
<td>≥92</td>
<td>&gt;130</td>
</tr>
</tbody>
</table>

Fig. 8. Distribution of microseism incidents in the working face.

Fig. 9. Profile of working face in the dip direction.

Fig. 10. Plane view of fracture characteristics of key strata “horizontal O-X”.

The relative spatial location of working face and far-field key strata is shown in Fig. 10. The arc-shaped block, namely the broken block marked in blue zone “C”, has a major impact on strata behaviors in the working face when the fracture of far-field key strata is illustrated in a form of “horizontal O-X”. But the area of the block “C” is far less than that of block “A” or “B”. This will cause block “C” to be lightly loaded and move down slowly. Under the protection of the block “C”, the far-field key strata have slight influence on the strata behaviors in the working face.

Table 1

The key strata suspension length, the limit span, and the roof weighting pace of borehole No. 1204.
“vertical O-X” breakage are called near-field key strata, and the ones of “horizontal O-X” breakage are called far-field key strata.

5.2. Mechanism of far-field rock strata movement

5.2.1. Far-field rock strata movement due to mining-induced pressure

The key strata far from the working face could form a stable “vousoir beam” structure which has the capacity of self-stabilization (see Fig. 11). With high mechanical performance and large breakage block length, the vousoir beam structure could withstand the loads imposed by the fissured zones below, only with a small rotary angle; therefore it has a minor influence on the working face pressure. The pressure of the working face during mining is mainly controlled by the key strata near the working face.

5.2.2. Far-field rock strata movement due to roadway near the goaf

Although the far-field key strata have a minor impact on the pressure applied to the working face, it has a major influence on the deformation of the roadways near the goaf. This is because the far-field key strata occur as a result of “horizontal O-X” breaking with the fracture direction parallel to the axis of the roadway working face, as shown in Fig. 12a. The breaking block exhibits a rotary movement under the effect of overlying strata loading. The rotary motion direction is perpendicular to the axis of the working face, and generates an extrusion force along the radial direction of tunnel cross-section, as illustrated in Fig. 12b. It shows that the far-field key strata breaking will have influence on the roadway stability near the goaf in the working face. The influence extent of far-field key strata breaking on the deformation of roadway along goaf is closely related to the spatial relations of roadway, key strata block, applied loads (the rotating speed of the breaking block), and means of roadway support.

For the working face 1 as shown in Fig. 13a, before the far-field key strata breaking, both ends of the hanging beam structure are basically similar. Thus beam breaking will form two blocks of A1 and B1 with a similar length. When the working face 2 near the goaf starts to advance, as the far-field key stratum constraint near the right side of breaking block B1 is greatly reduced, the breaking block length will be greater than the block length of far-field of key strata of working face 1. Then the breaking block length of two breaking blocks of A2 and B2 follows $L_{A2} > L_{B2}$, as shown in Fig. 13. In this case, the load of breaking block A2 is greatly increased as compared with that of block A1. At the same time, the lower strata rotate under the action of overlying breaking block, as shown in Fig. 13a, and a nonuniform pressure distribution is formed in the coal pillar, which leads to occurrence of uneven deformation. The pressure of the coal pillar near the goaf side is small while the coal pillar pressure near the working face is large, namely $F > f$, so the roadway along the goaf deforms under high stress. The larger the strata thickness controlled by far-field key strata, the larger the rotational velocity of breaking block and the stronger the dynamic responses under the action of overlying load. Thus rockburst disasters in the roadway can be induced. Fig. 13b shows the impact effect of far-field key strata breaking on the deformation of roadway along the goaf when the third mining face advances (i.e. the second working face near the goaf). The deformation and mechanism are basically the same as that of the second mining face (i.e. the first working face near the goaf).

6. Experimental verification on the mechanism of large-space structural movement of overburden rocks induced by mining pressure

6.1. Modeling scheme

To analyze the mining-induced pressure imposed by the key strata fracture movement, physical simulation experiments are conducted. The plane-stress model under the condition of gravity-driven forces is selected. The model dimensions are 500 cm $\times$ 30 cm (length $\times$ width) (see Figs. 13–16). Geometric similarity ratio of model is 1:100, bulk density similarity ratio is 1:156, and stress similarity ratio is 1:156. The rock-like materials are made of river sand aggregate, gypsum and calcium carbonate. A layer of mica is set at the junction between the layers. The materials of each layer are shown in Table 2.

6.2. Experimental results analysis

The moments of key strata MKS, KS2 and KS1 before and after breaking can be observed in Fig. 17. The number and layout of stressometers are shown in Fig. 17b, where stress meter $^13(3-4)$ is located at the top interface of the KS1, stress meter $^26(5-1)$ is set in the bottom interface of KS2, and stress meter $^29(6-6)$ is arranged at the top interface of the KS2. The stress transmission of three key strata can be revealed by stress evolution during fracturing process. The supercharging effect of each key layer on underlaying strata is regarded as the judgment index to evaluate the effect of key strata on the mining pressure development in the working face.

According to Fig. 18a, it is known that:

1. Three key strata KS1, KS2 and MKS were broken in sequence macroscopically. The position of three initial displacement points shows that KS1 moves first, followed by KS2 and MKS.
2. The relationship of moving speed of three key strata is shown in area A (green line). After the breakage of three key strata, their rotary speeds are significantly different as the rotary speed of MKS is the largest, followed by KS2 and KS1, $\overset{6}{\text{MKS}} > \overset{4}{\text{KS2}} > \overset{2}{\text{KS1}}$.

According to Fig. 18b, it is clear that:

1. The stresses recorded by stressometer $^26(5-1)$ rise sharply, while those recorded by stressometer $^13(3-4)$ decline, indicating that KS2 has experienced a relatively large stress imposed by the underlying strata. However, the loading

Fig. 11. Three-dimensional (3D) fracture characteristics of key strata structure.
The direction of crack within horizontal O-X

Roadway on goaf side

(a) Planar graph. The symbol (1) presents the goaf, and (2) denotes the working face.

Far-field key stratum structure

(b) Profile map.

**Fig. 12.** Key layer “horizontal O-X” breaking and its effect on roadway near the goaf.

(a)

(b)

**Fig. 13.** Strata movement mechanism of roadway near the goaf.

**Fig. 14.** Diagram of physical modeling.
pressure in KS2 is not completely transferred to KS1 due to the movement hysteresis in presence of multi-level strata.

(2) The initial displacement point of KS2 intersects that of stressometer #26(5-1). This means that KS2 has released a certain percentage of stress to the underlying stratum. It also shows that the initial displacement point of MKS is located within the rising stage of stressometer #39(6-6), but the stress increase rate of #26(5-1) is larger than that of stressometer #39(6-6), indicating the pressure transmission between KS2 and MKS is not effective, and a compaction effect induced by KS2 on the underlying stratum can be observed. In other words, although there is a sequence existing in motion of key strata KS1, KS2, MKS, i.e. $\theta_{\text{MKS}} > \theta_{\text{KS2}} > \theta_{\text{KS1}}$, the total rotary angle of three key strata would satisfy $\theta_{\text{MKS}} = \theta_{\text{KS2}} = \theta_{\text{KS1}}$. In the next movement, KS2 would has certain pressure effect on KS1, as the stress curve rises significantly, but the pressure effect of MKS on KS2 is not obvious. The stress increase rate is much smaller, which is related to the smaller overlying loads induced by MKS.

In other words, although there is a sequence existing in motion of key strata KS1, KS2, MKS, i.e. $\theta_{\text{MKS}} > \theta_{\text{KS2}} > \theta_{\text{KS1}}$, the total rotary angle of three key strata would satisfy $\theta_{\text{MKS}} = \theta_{\text{KS2}} = \theta_{\text{KS1}}$. In the next movement, KS2 would have certain pressure effect on KS1, as the stress curve rises significantly, but the pressure effect of MKS on KS2 is not obvious. The stress increase rate is much smaller, which is related to the smaller overlying loads induced by MKS.

On the basis of the judgment index aforementioned, it can be noted that KS2 causes a larger effect on the working face pressure while MKS has a smaller influence on mining pressure upon this breakage stage.

According to the study (Qian et al., 2003), the strata show the characters of group breaking due to the controlling effects induced by the key strata. As shown in Fig. 16, the breaking lengths of three key strata KS1, KS2 and MKS are 34.5 cm, 41.4 cm and 67.06 cm, respectively. Considering the group breaking character and the rotational velocity ratios of three blocks at breaking (Fig. 18a), the ratio of three key strata’ energy released during breaking can be calculated. The result yields $E_{\text{KS2}}:E_{\text{KS1}}:E_{\text{MKS}} = 1:1.36:4.38$. This shows that huge energy released by the main key strata (far-field) will cause excessive deformation of the rocks surrounding the roadway, which can result in roadway failure.
7. Strata control countermeasures of stope mining

To avoid the occurrence of strong strata behaviors in extra-thick coal seam, a roof pre-control technology of “near- to far-field collaborative roof weakening based on surface drilling fracturing and underground roof pre-splitting” is proposed, as shown in Fig. 19.

The key of this technology is implemented through the vertical and L-typed fracturing boreholes from the surface to change the stress state of the key strata in far field (more than 80 m from the roof of coal seam) (see Fig. 19a). First, the vertical drilling was conducted, and then the horizontal drilling was considered when the vertical distance reached the target position. In this circumstance, energy accumulated in the key strata can be released at the same time, and the stress transferring to the working face is reduced during key strata breaking. The support effect of roadway after fracturing of far-field key strata by hydraulic fracturing is shown in Fig. 20.

Meanwhile, using layered blasting technology for the hard roof and directional hydraulic fracturing pressure of 60 MPa, the pre-splitting can be realized on the key strata in the near field of working face (about 30 m from the roof of coal seam). Thus the first caving, periodic weighting interval, and strength of the basic roof can be reduced.

8. Conclusions

When mining the Carboniferous extra-thick coal seams Nos. 3–5 with fully-mechanized top-coal caving method in Datong mine area, a huge mined-out area was formed, and it causes a large-scale strata movement. The traditional strata pressure theory cannot fully explain the strong strata behaviors in Datong extra-thick coal seams using fully-mechanized top-coal caving method, as the effect of far-field key strata breakage on strata behaviors cannot be taken into account.
The far-field key strata in extra-thick coal seams with fully-mechanized top-coal caving method will form “masonry beam” structure represented by “horizontal O-X” breaking. While it has a minor effect on rock pressure in the goaf, the rotary movement of the key strata breaking block can cause squeezing effect on the surrounding rocks along radial direction, which can cause excessive deformation and damage to the free surface of roadway. A roof pre-control technology of “near-to far-field collaborative roof weakening based on surface drilling fracturing and underground roof pre-splitting” is proposed which could effectively solve the problem of strong strata behaviors during mining extra-thick coal seams.

Conflict of interest

The author wishes to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This work is supported by the Special Funding Projects of “Sanjin Scholars” Supporting Plan (Grant No. 2050205).

References