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ORIGINAL ARTICLE

Analysis of developmental features and causes of the ground cracks induced by oversized working face mining in an aeolian sand area

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Abstract In order to satisfy the energy demand of China, it is an effective way to exploit coal resources efficiently in western China. When a coal seam with a shallow burial depth is mined on a large working face with width of 300 m in a semi-desert aeolian sand area of western China, the induced subsidence and damage of ground surface are remarkably different from those induced by a traditional mining condition. By taking Working Face 12,406 of Bulianta Coalmine in Shendong Mining Area as an example, this paper, based on actual measurement data, analysed the developmental features and causes of ground surface racks. Research results showed that the shape of the static crack in the peripheral area on the working face was very similar to that contained in the actual measurement results of other areas; specifically, such static crack was arc-shaped and the actually measured static crack angle was 84.5°. However, the dynamic crack above the working face took on uniqueness in two developmental cycles (expansion to restoration). This phenomenon is not available in other research areas. Starting from the structure of rock strata, this paper analysed the two developmental cycles of dynamic cracks according to the periodic fracture theory of key stratum and verified the results of theoretical analysis by employing the similar material model.

Keywords Aeolian sand · Shallow burial depth · Oversized working face · Ground surface crack · Secondary development

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Introduction

Coal resources account for about 68% of China's total primary energy resources. In 2015, the annual coal demand of China exceeded four billion tons. Objectively, the booming coal demand calls for large-scale and high-intensity exploitation of coal resources. Undoubtedly, large-scale exploitation of coal resources will do harm to the environments of ground surface. As a typical form of destruction, the cracks induced by coal mining make particularly severe impacts upon ecological environments and are always the focus of researches among the researchers of mining subsidence.

Through a great deal of field observation and theoretical analyses, the researchers have attained a common view on the generation, expansion and formation process of the ground surface cracks induced by coal mining. When the ground surface deformation induced by coal mining reaches a certain degree, cracks begin to be generated on the ground surface above the worked-out section. With continuous advance of the working face, the forms and positions of cracks are also changed gradually. Specifically, (1) a peripheral crack on the working face undergoes a variation process of generation to expansion, finally forming a permanent open crack; (2) a crack above the working face undergoes a variation process of generation, expansion to restoration, finally forming a crack with a width far smaller than the historical maximum width, and even a portion of the original crack area is extruded and swollen. They described the start position, end position and dynamic development position of a crack by such definitions as the crack angle, dynamic crack angle (advance crack angle) and crack restoration angle (Guo et al. 2010; De Graff and Ch Romesburg 1981; Yu 1996; Wu et al. 1997a), determined the distribution range of ground surface cracks based on the probability integral method model, Mohr–Hooke shear strength criteria and general Hooke law (Wu et al. 1997b, 2009) and discussed the methods of calculating the extreme development depth based on the assumption that only one crack is induced by coal mining and the subsidiary stress is centrally released (Wu et al. 2010).

In addition, research results showed that the shape and development process of the crack induced by coal mining are affected by the nature of surface soil layer. For example, clay is more prone to causing a crack than loess when the ground surface deformation is the same. Loess is characterized by a great rhythmicity. Therefore, a crack in a loess area has a far larger development depth than a crack in a clay area (Yu et al. 2008).

As compared with other existing researches, this paper focused on the observation and research of the development condition of ground surface cracks arising from the mining of coal seams with a shallow burial depth on a super large working face in semi-desert aeolian sand areas of western China. Observation results showed that the dynamic crack above the working face in the research area takes on two developmental cycles (expansion–restoration). This paper conducted field research on this type of crack development and tried to find out the reason therefor.

Research area

Bulianta Coalmine is within the territory of Wulanmulun Town, EjinHoro Banner, Erdos City, Inner Mongolia, more specifically, in the northeast of Bulian Mine of Shengdong Coalfield. The overall landform of the research area is characterized by high east and low west and is fluctuated gently. The elevation of ground surface ranges from 1080 to 1300 m, and the average elevation of ground surface is about 1200 m. The ground surface is mainly covered by aeolian sand. The ground vegetation mainly includes the small poplar trees and Salix psammophila artificially planted to withstand sandstorms, and wild native drought-resistant weeds.

Bulianta Coalmine utilized the adit plus inclined shaft mode, along with the longwall mining method. Working Face 12,406 belongs to the fourth mining area. The ground elevation ranges from 1238 to 1307 m, the elevation of the coal floor ranges from 1074 to 1094 m, the strike length of the working face is 3592 m, the dip width is 300 m, and the ground surface is basically covered by the unconsolidated formation of aeolian sand. To the southwest of this working face is the Working Face 12,405 under stoping, and to the northeast of this working face is the Working Face 12,407 under preparation. Figure 1 shows the positions of working faces and corresponding conditions on the ground surface.

For Working Face 12,406, the mining depth ranges from 190 to 220 m, the depth of bed rocks ranges from 180 to 200 m, and the depth of the unconsolidated formation ranges from 10 to 25 m. Coal Seams one and two are mined because they are stable and simply structured. The dip angle ranges from 1° to 3°, and the occurrence thickness ranges from 4.19 to 5.56 m (4.81 m averagely). This working face began to be stopped in April 2011 and was stopped completely in December 2011 with a daily advance of about 13 m.

For Working Face 12,406, the substrate of the regional tectonic unit is the firm crystalline rock series of pre-Sinian system, and the entire geological development process before/after coal formation inherits the stability of the deep substrate. The coal measure stratum and overlying rock stratum are highly integrated into one whole, which possesses high compressive, tensile and bending strength. The overlying rock stratum comprises multiple rock substrata, which are dominated by high-strength rock substrata with a thickness of at least 2.0 m and usually exclude soft rock substrata of thick stratum (Sun 2008). Table 1 describes the structure and physic-mechanical properties of the rock stratum (Zhang et al. 2003).

Developmental status of ground surface cracks in the research areas

Crack observation method

Deploy an observation station above the working face in question, determine the horizontal coordinates and elevations of station points via the second-order traverse and fourth-order levelling, and set up a total station at the station point, so as to measure the planimetric position of the crack. The crack width has been measured in the following way: (1) selecting typical positions, (2) using a steel ruler to measure the width repeatedly, (3) selecting the average width value. Figure 2 shows the layout drawing for the measurement points. Points K1–K8 are the control points beyond the scope of influence by coal mining, and Points B1–B45 and Points A1–A45 are station points (Hu et al. 2014).

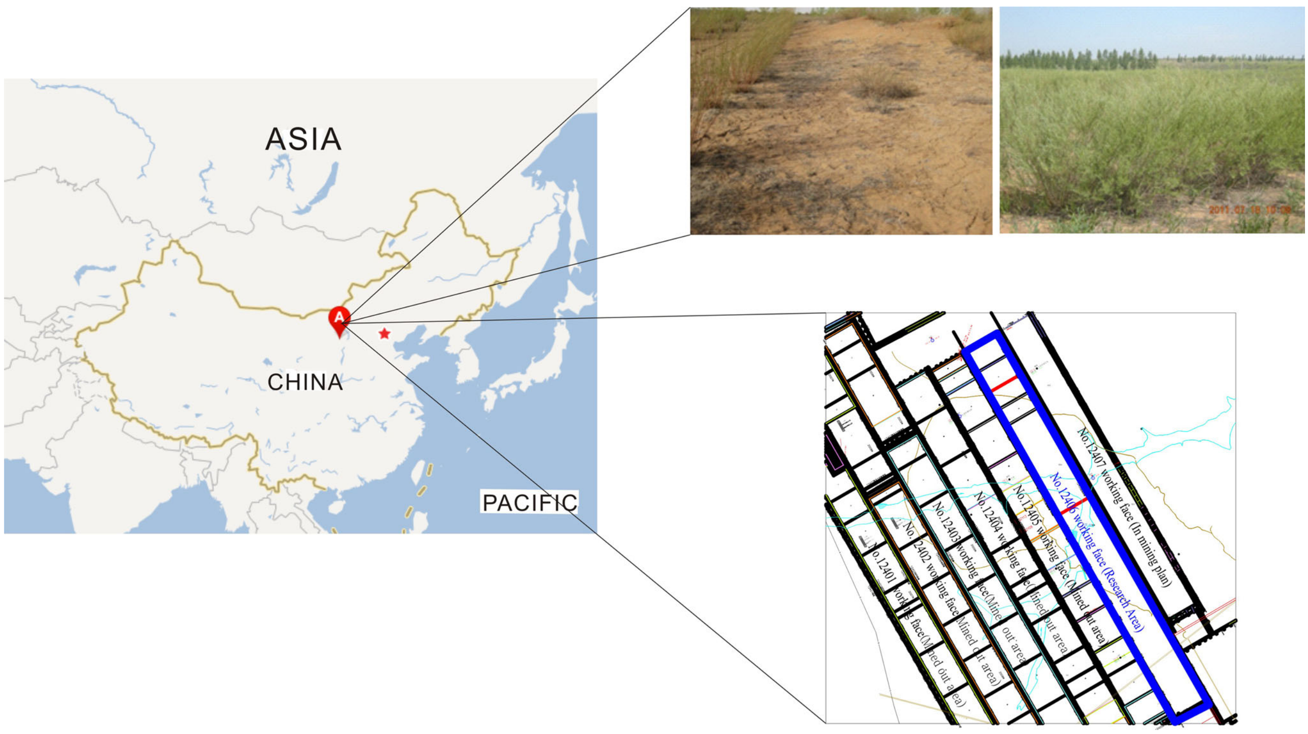


Fig. 1 Research area

Distribution pattern of planimetric positions of cracks

In order to describe the distribution and variation process of cracks conveniently, the ground surface cracks arising from coal mining are classified into static cracks and dynamic cracks. A static crack refers to a crack whose width is increased gradually with the mining of the working face in the peripheral area and reaches a stable value at a certain degree. A dynamic crack refers to a crack that undergoes the periodic variation of generation, expansion to restoration in front of the advance position of the working face, and is basically closed finally.

During the days of May 17–26, 2011, the researchers completely measured the static cracks nearby the open-off cut and at the edges of uphill/downhill boundaries. Every day, they tracked the expansion and development process of the dynamic cracks above the working face in real time. Figure 3 shows the measured planimetric positions of cracks, advance positions of working face and numbers of typical dynamic cracks. In Fig. 3, the violet area is the monitoring area for dynamic cracks, and the red cracks are the cracks that are measured in terms of width variation.

1. The static cracks nearby the open-off cut and at the uphill/downhill positions are developed in the form of a few long cracks, the cracks in three directions can almost be connected into an arc, and the cracks are distributed within a narrow scope.
2. The static cracks nearby the open-off cut are extended parallel with the dip direction of the working face, the maximum crack length can reach the dip length of the working face, the cracks are developed to be very wide, the average interval between the well-developed cracks is about 15 m, and the interval between the innermost crack and outermost crack is about 56 m. When the interval between two is less than 2 m, the in-between part will suffer overall subsidence.
3. The static cracks on the uphill/downhill boundaries of the working face are extended parallel to the strike direction of the working face, the developmental width is between that of the static cracks and dynamic cracks nearby the open-off cut, the interval between the innermost static crack and outermost static crack is about 50 m, the cracks are extended continuously, and the forefront of the extension direction is shrunk to above the working face, tending to connect to a developing dynamic crack. The static crack nearby the open-off cut is 19.35 m away outside the open-off cut, and the crack angle is 84.5°.
4. The dynamic cracks in front of the advance position of the stoping face are developed in the form of dense short cracks. With the advance of the working face, new cracks are generated successively. The length of the generated cracks is gradually increased, and the

Table 1 Strata structure and physical mechanical properties

No.	Rock strata	Rock thickness (m)	Bulk density (γ, kN/m^3)	Elastic modulus (E, GPa)	Remarks	Broken step (m)
1	Weathered sandstone	13.5	17	0		
2	Glutenite	5.32	20	8		
3	Medium-grained sandstone	49.83	25.2	41.2	KS II	32.2
4	Coarse-grained sandstone	0.46	25	39.7		
5	Mudstone	1.71	24	18		
6	Medium-grained sandstone	10.96	25.2	41.2		
7	Silty mudstone	2.47	23.8	40		
8	Glutenite	2.43	20	8		
9	Fine-grained sandstone	1.86	25.2	43.4		
10	Medium-grained sandstone	2.44	25.2	41.2		
11	Glutenite	23	20	8		
12	Siltstone	2.05	24	18		
13	Fine-grained sandstone	2.93	25.2	43.4		
14	Medium-grained sandstone	2.31	25.2	41.2		
15	Siltstone	5.03	24	18		
16	Medium-grained sandstone	2.29	25.2	41.2		
17	Siltstone	2.03	24	18		
18	Coarse-grained sandstone	2.76	25	39.7		
19	Siltstone	2.82	24	18		
20	Silty mudstone	18.2	23.8	40		
21	Medium-grained sandstone	1.47	25.2	41.2		
22	Silty mudstone	23.01	23.8	40	KS I	16.9
23	Medium-grained sandstone	4.3	25.2	41.2		
24	Silty mudstone	3.82	23.8	40		
25	Fine-grained sandstone	4.18	25.2	43.4		
26	Silty mudstone	5.72	23.8	40		
27	Fine-grained sandstone	2.25	25.2	43.4		
28	Coal	4.5	13	10		
29	Silty mudstone	5	23.8	40		

width of them undergoes a process of generation, expansion, restoration, re-expansion till re-restoration.

5. Dynamic cracks are extended perpendicularly to the strike direction of the working face. These cracks have a self-repair capability. The process of generation to closing is closely correlated with the mining progress of the underground face. Most of the cracks are distributed nearby the midline of strike. Between the connected static and dynamic cracks, there are a few bow-bending dynamic cracks.
6. The advance face distance of dynamic cracks ranges from 5.58 to 31.39 m (14.99 m averagely), and the forefront crack angle ranges from 81.1° to 88.4°. The cracks are very narrow and take on a straight-line shape, the maximum crack length is 42.33 m, and the average interval between cracks ranges from 3.31 m to 7.25 m. Table 2 lists the basic data of the cracks. As shown in Table 2, the advanced distance of the last three days is relatively long. For the three days, the observation was conducted in a forest. Tree roots have a certain inhibitory effect upon the formation of ground surface cracks (Guo 2013).

Measurement of crack width

Measuring the width of static cracks

With the advance of the working face, the static cracks in the edge area of the working face undergo a process of generation, expansion to stabilization. The researchers measured the width of the stabilized typical static cracks in the peripheral area of the working face. Table 3 lists the measurement results.

As shown in Table 3, the maximum crack width reaches 58.8 mm and the crack width is developed very remarkably.

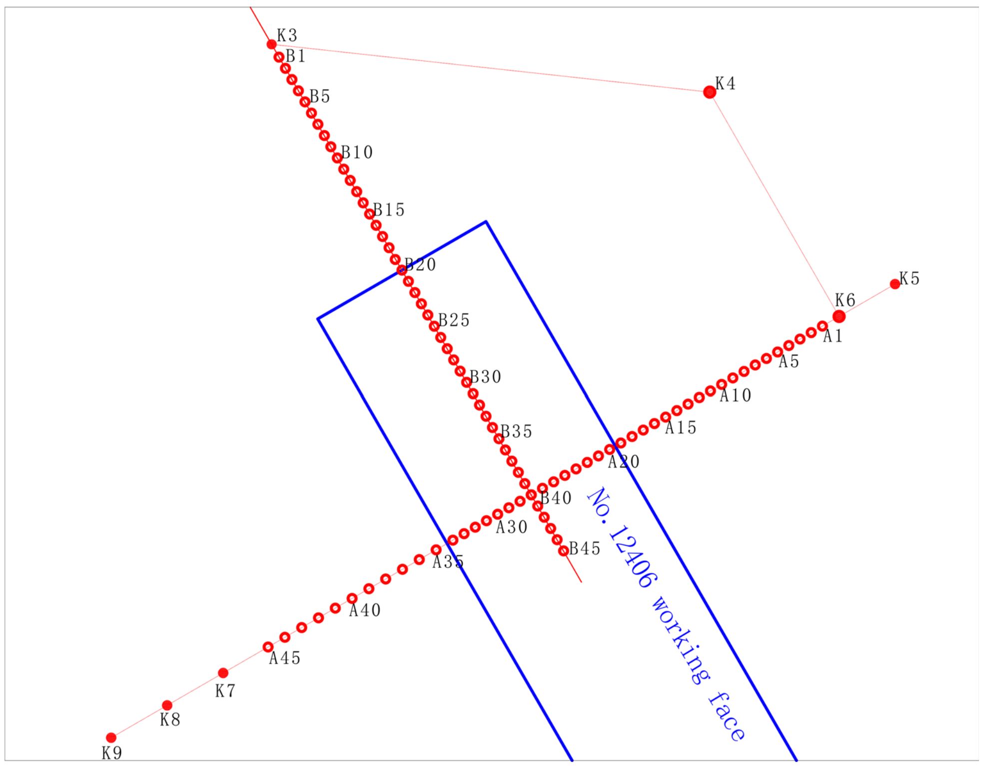


Fig. 2 Layout of fissure observation reference line

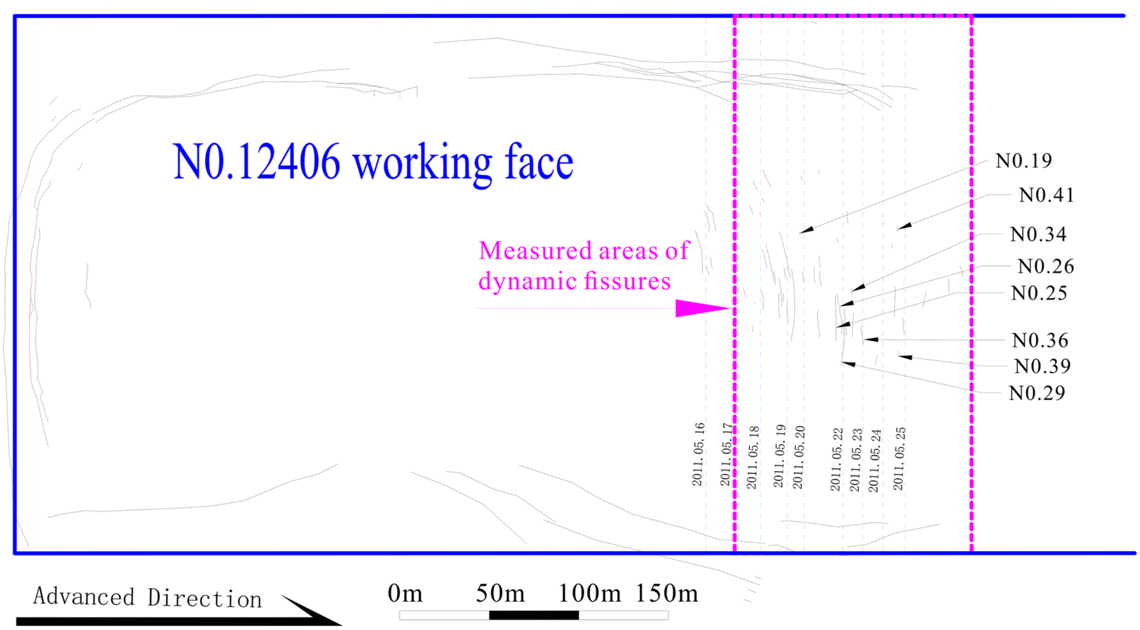


Fig. 3 Distribution pattern of planimetric positions of cracks

Measuring the width of dynamic cracks

With the advance of the working face, the researchers measured the variation of width of some dynamic cracks above the working face. Figure 3 shows the selected typical crack positions.

Table 4 describes the periodic variation of crack width, and Fig. 4 shows the time-varying law of crack width.

According to Table 3 and Fig. 4, the dynamic cracks above the working face undergo a process of development, closing, stabilization, re-development to re-closing, and the whole evolution cycle is about 18 days. During the two development–closing processes, the maximum crack width

Table 2 Dynamic fissure study

Measurement date	Fissure length (m)	Fissure interval (m)	Advanced distance (m)	Fissure angle (°)
5-17	24.22	2.59–6.78	12.16	86.5
5-18	16.54	2.20–9.13	11.90	86.6
5-19	42.33	5.59–15.42	17.07	85.1
5-20	15.92	–	5.58	88.4
5-21	25.25	1.57–8.42	11.79	86.6
5-22	31.44	3.05–7.98	18.36	84.7
5-23	7.57	6.52–7.71	18.66	84.7
5-24	17.33	4.62–5.78	26.30	82.5
5-25	9.37	5.16–8.77	22.86	83.5
5-26	8.46	7.04	31.39	81.1

Table 3 Width of stabilized cracks

No.	Width (mm)	Crack number	Width (mm)	Crack number	Width (mm)
CP01	22.5	CP15	18.1	KP03	7.3
CP02	58.8	CP16	22.4	KP04	22.5
CP03	38.4	CP17	35.7	KP05	17.4
CP04	38.2	CP18	14.5	KP06	23.6
CP05	19.8	CP19	32.1	KP07	16.8
CP06	26.7	CP20	39.3	KP08	32.6
CP07	28.1	CP21	18.8	KP09	13.2
CP08	31.7	CP22	34.7	KP10	16.3
CP09	45.6	CP23	22.5	KP11	21.2
CP10	23.3	CP24	19.5	KP12	17.2
CP11	43.4	CP25	20.4	KP13	17.5
CP12	26.7	KP01	20.1	KP14	18.6
CP13	21.5	KP02	13.5	KP15	27.2
CP14	23.6				

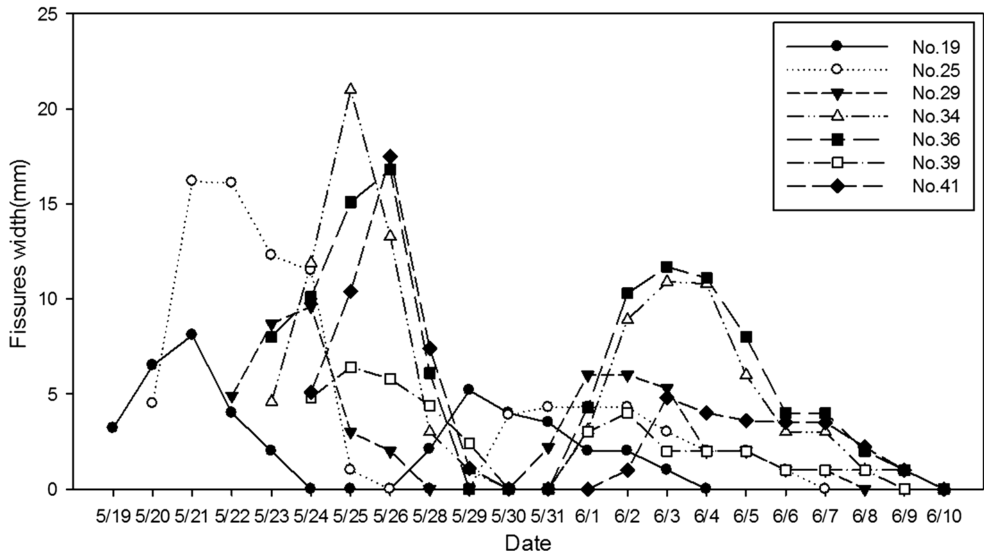
Table 4 Cracks in all stages time of the development cycle

No.	Development time (days)	Closing time (days)	Stabilization time (days)	Re-development time (days)	Re-closing time (days)	Total (days)
19	4	2	3	3	5	17
25	4	2	4	4	5	19
29	3	2	4	3	6	18
34	4	3	1	3	7	18
39	3	4	1	1	8	17
41	3	4	2	1	7	17
Total	3–4	2–4	1–4	1–4	5–8	17–19

during the first development was greater than that during the second development. Specifically, the maximum crack width in the first development was 22 mm of Crack 34, and the maximum crack width was 13 mm of Crack 36.

Existing research results showed that the dynamic ground surface cracks induced by traditional mining modes all undergo one cycle of development to stabilization. In contrast, the dynamic cracks available in the research area undergo two development cycles uniquely. Therefore, the following section will expound on the developmental process of such dynamic cracks in detail.

Fig. 4 Relationship between fissures width and date



Causal analyses for secondary development of dynamic cracks

Positional relation between crack width and advance of working face

Actual measurement data showed that the different positions of the same crack share the same law of width variation. Therefore, the researchers selected one position for each crack to study the correlation between the variation of crack width and advancing position of the working face.

The working face is advanced rapidly (specifically, it is advanced for more than 10 m between two observations), and the distance between each crack and the advancing position of the working face varies by observation. For the convenience of comparison, the observation data in Fig. 4 are subjected to linear interpolation and resampling at a regular interval of 5 m. Figure 5 shows the correlation between crack width and advancing position of the working face.

As shown in Fig. 5, each crack is generated about 5 m away in front of the advancing position of the working face, the crack width reaches the maximum value at the position where the working face is advanced for about 25 m, each crack is closed at the position where the working face is advanced for about 60 m, each crack undergoes secondary generation at the position where the working face is advanced for about 100 m, each secondarily generated crack reaches the maximum width at the position where the working face is advanced for 150 m, and each secondarily generated crack is completely closed at the position where the working face is advanced for about 220 m. In other words, the working face is advanced for about 60 m during the first developmental cycle and is advanced for about 120 m during the second developmental cycle.

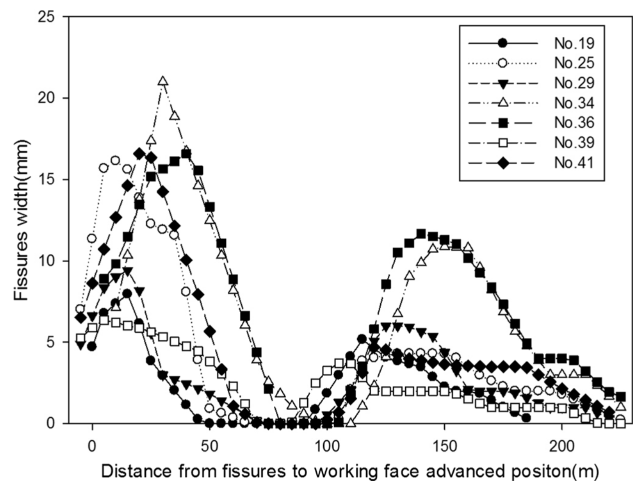


Fig. 5 Relationship between fissures width and working face position

Theoretical analyses for the causes of secondary expansion and development of dynamic cracks

Actual measurement results showed that the developmental process of the dynamic ground surface cracks in the research area differs from that in other areas remarkably. Specifically, the dynamic ground surface cracks in the research area will undergo secondary development. By focusing on the structure of rock strata, the following section analyses the causes of the secondary development of such cracks.

According to Table 1, the research area is characterized by typical shallow mining of hard rock stratum, and there exist two obvious hard and thick rock strata at two positions (43 and 180 m above the coal seam). According to the key stratum theory (Qian et al. 2003; Xu and Qian 2000), such structure of rock strata results in the support structure of compound key stratum. With continuous advance of the working face, the compound key stratum takes on different cracking cycles. Figure 6 shows the impacts of the periodic cracking process upon the development of a single ground surface crack.

When the mining of the working face results in the fracture of Key Stratum I (KS I), cracks are generated on the ground surface. Figure 6 shows the position A of a dynamic crack. With the advance of the working face, Key Stratum I is fractured periodically, so the crack is enlarged constantly, as shown in the position B in Fig. 6. With continuous advance of the working face, the impacts of Key Stratum I upon the crack gradually disappear, and the crack is closed, as shown in the position C in Fig. 6. With further advance of the working face, Key Stratum II (KS II) is fractured, and thus, the closed crack is secondarily opened, as shown in the position D in Fig. 6. With the forward expansion of periodic fracture of Key Stratum II, the crack undergoes a secondary expansion and restoration process, as shown in the positions E and F in Fig. 6.

According to the distribution of rock strata and physic-mechanical properties of rocks in Table 1, the researchers applied the key stratum theory to calculate the key strata in the research area and their intervals of roof breaking. The calculation results showed that the 3rd and 22nd rock strata in Table 1 are key strata, and the corresponding intervals of roof braking are 32.2 and 16.9 m, respectively. The interval of roof breaking of Key Stratum II is about twice as much as that of Key Stratum I. Likewise, the second expansion and development distance of the crack is about twice as much as the first expansion and development distance of the crack, as shown in Fig. 5.

Before Key Stratum II is fractured, some of the space released by coal mining has been absorbed by the rock–stratum bulking induced by the fracture of Key Stratum I while some of such space has been released to the ground surface. Therefore, the mining deformation induced by the fracture of Key Stratum II is smaller than that induced by the fracture of Key Stratum I. Correspondingly, the intensity of the secondary crack expansion and development is lower than that of the first crack expansion and development.

The periodic fracture of the rock stratum overlying the worked-out section will result in periodic fluctuation of the subsidence value and rate of ground surface. This phenomenon has been verified by the observation results available under the same geological and mining conditions (Yi 2008). Existing results showed that when the time difference of subsidence observation is less than three days, the periodic fluctuation of subsidence rate of ground surface can be determined via observed values. Unfortunately, the researchers have not observed intensively the subsidence of ground surface in the research area, making it impossible to verify the actual measurement data.

Similar material model analyses for secondary expansion and development of dynamic cracks

In order to further verify the law of rock–stratum fracture induced by coal mining on a super large working face in an aeolian area and the impacts upon the development of ground surface cracks, this paper conducted a similar material model experiment according to the drillhole column and physic-mechanical properties of rock stratum on Working Face 12,406 of Bulianta Coalmine contained in Table 1. The geometric similarity ratio of the model was 1:200. During the model experiment, the thin fourth and fifth rock strata were merged, and the physic-mechanical properties were measured according to the interbedding of mud rocks and siltstones. Table 5 describes the mixing ratios of experimental materials calculated according to the dynamic similarity ratio.

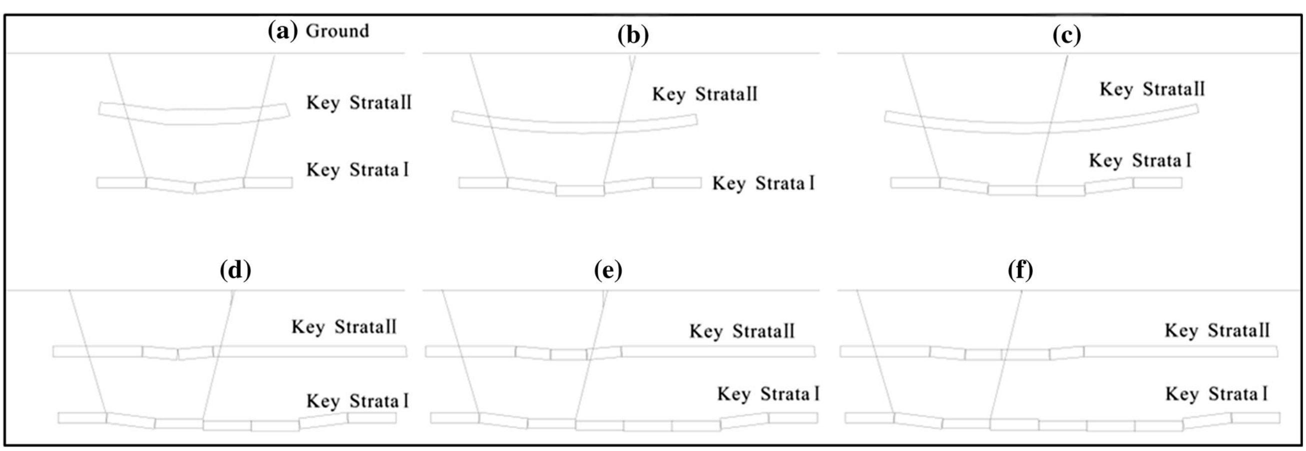


Fig. 6 Crack width development according to the breaks of compound key stratum

After the similar materials had been fully mixed according to the composition in Table 5, each layer was sequentially paved into the model frame. This model is 4 m long and 10 cm wide and equivalent to full subsidence in the tendency direction. We mainly study the strata movement in the strike direction. The mining thickness is 2.25 cm and mining speed 5 cm/h. Each exploitation lasted for 10 min, after which model deformation was recorded by taking pictures and measuring the periodic fracture of strata. The whole mining process lasted for a total of 3 days, and two extra groups of photographs were taken before and after coal mining as supplementary information. Figure 7 shows the actual model.

Due to dimensional limitation, the ground surface cracks on the model are few and tiny, so it is very difficult to acquire the information about the variation process of crack width. Therefore, similar material simulation mainly focused on the step-by-step fracture process of two key strata. Figure 8 shows the fracture status of two key strata with continuous advance of the working face.

With continuous advance of the working face, the caving fracture zone induced by coal mining is constantly developed upwards, thus causing the fracture of Key Stratum I. During the periodic fracture of Key Stratum I, Key Stratum II undergoes a developmental process of overall bending, initial fracture to periodic fracture. The law on fracture of the two key strata coincides well with the theoretical deduction in Fig. 6.

According to the geological and mining conditions of Bulianta Coalmine, Ju and Xu (2013) conducted similar

Table 5 Mixing ratios of experimental material model

No.	Thickness (cm)	Quantity	Sand (kg)	Mica (kg)	Parget (kg)	Calcium carbonate (kg)	Water (kg)	Saw dust (kg)
1	6.7	6	14.09	1.42	0.22	0.09	1.58	
2	2.6	2	16.31	1.57	0.28	0.28	1.84	
3	24.9	25	12.28	1.13	0.35	0.35	1.41	
4	1	1	11.98	1.63	0.28	0.28	1.42	
5	5.4	5	13.32	1.22	0.38	0.38	1.53	
6	1.2	1	14.80	1.36	0.43	0.43	1.70	
7	1.2	1	15.05	1.45	0.26	0.26	1.70	
8	0.9	1	11.10	1.02	0.32	0.32	1.28	
9	1.2	1	14.80	1.36	0.43	0.43	1.70	
10	11.5	11	13.12	1.26	0.22	0.22	1.48	
11	1	1	12.54	1.20	0.30	0.13	1.42	
12	1.4	1	17.27	1.59	0.50	0.50	1.99	
13	1.1	1	13.57	1.25	0.39	0.39	1.56	
14	2.5	2	15.68	1.51	0.37	0.16	1.77	
15	1.1	1	13.57	1.25	0.39	0.39	1.56	
16	1	1	12.54	1.20	0.30	0.13	1.42	
17	1.3	1	15.20	2.12	0.33	0.77	1.84	
18	1.4	1	17.56	1.69	0.42	0.18	1.99	
19	9.1	9	11.82	1.65	0.26	0.60	1.43	
20	0.7	1	8.63	0.79	0.25	0.25	0.99	
21	11.5	11	12.23	1.70	0.27	0.62	1.48	
22	2.1	2	12.95	1.19	0.37	0.37	1.49	
23	1.9	2	11.11	1.55	0.24	0.57	1.35	
24	2	2	12.33	1.13	0.35	0.35	1.42	
25	2.8	3	10.91	1.52	0.24	0.56	1.32	
26	1.1	1	13.57	1.25	0.39	0.39	1.56	
27	2.2	2	13.80	1.33	0.23	0.23	1.56	0.32
28	2.5	2	14.62	2.04	0.32	0.74	1.78	
Total	103.3	98						

The thickness of every quantity is 1 cm

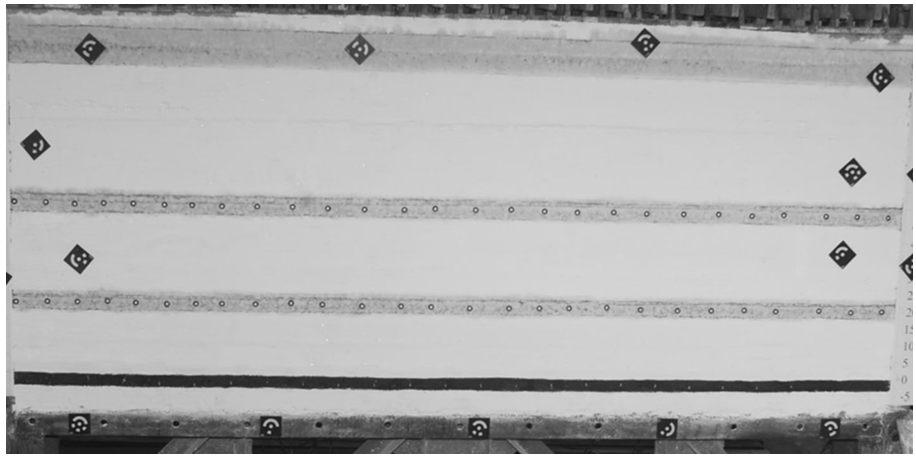


Fig. 7 Similar material model

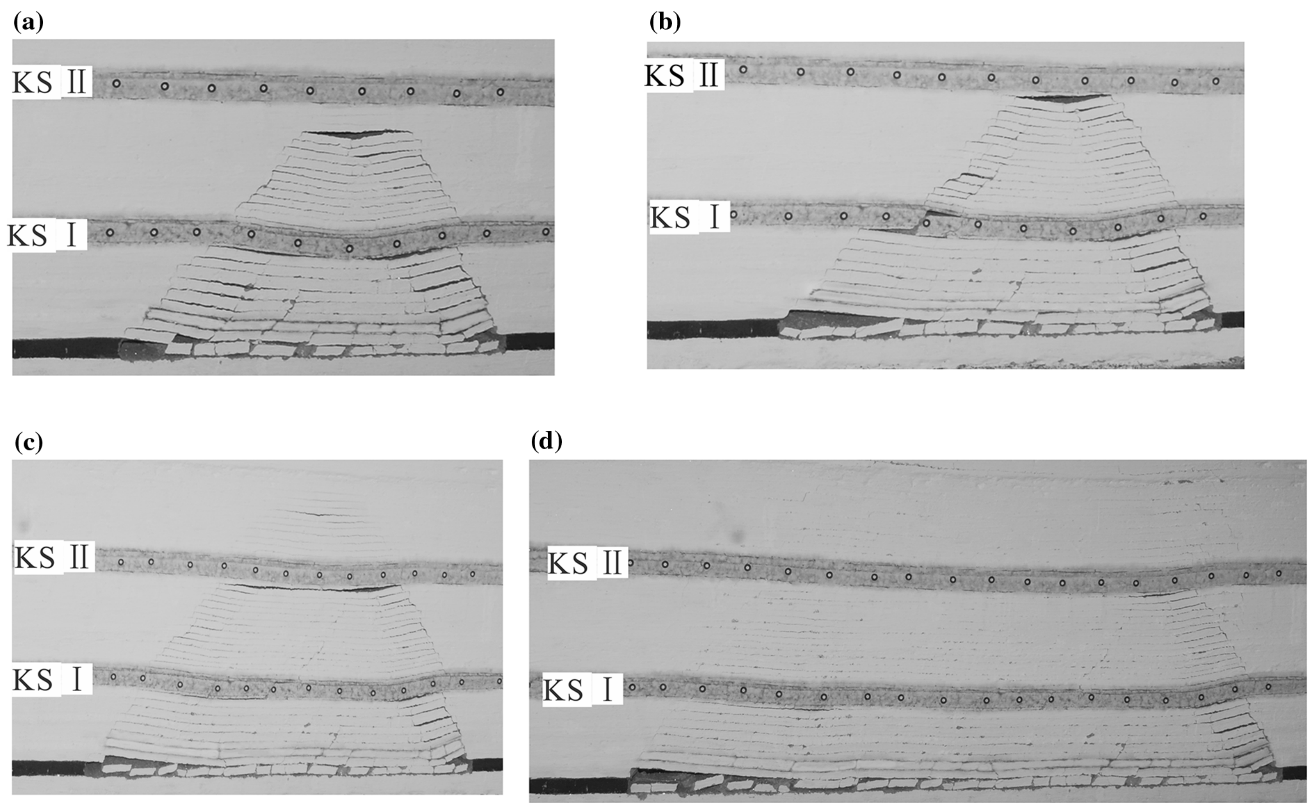


Fig. 8 Experimental results about the break of KS. **a** KS I bent and subsidence; **b** KS I broke; **c** KS I broke, KS II bent and subsided; and **d** KS II broke

material simulation for the fracture of the two key strata, so as to study the changes in mine pressure. Figure 9 shows the fracture process of the key strata.

The results of similar material simulation in Fig. 9 also showed the following: during the fracture of the two key strata overlying the coal seam of Bulianta Coalmine, there surely exist two different fracture cycles, and the fracture cycle of the lower key stratum is ahead of that of the upper key stratum. To a certain degree, the experimental results confirm the correctness of the results of theoretical analysis.

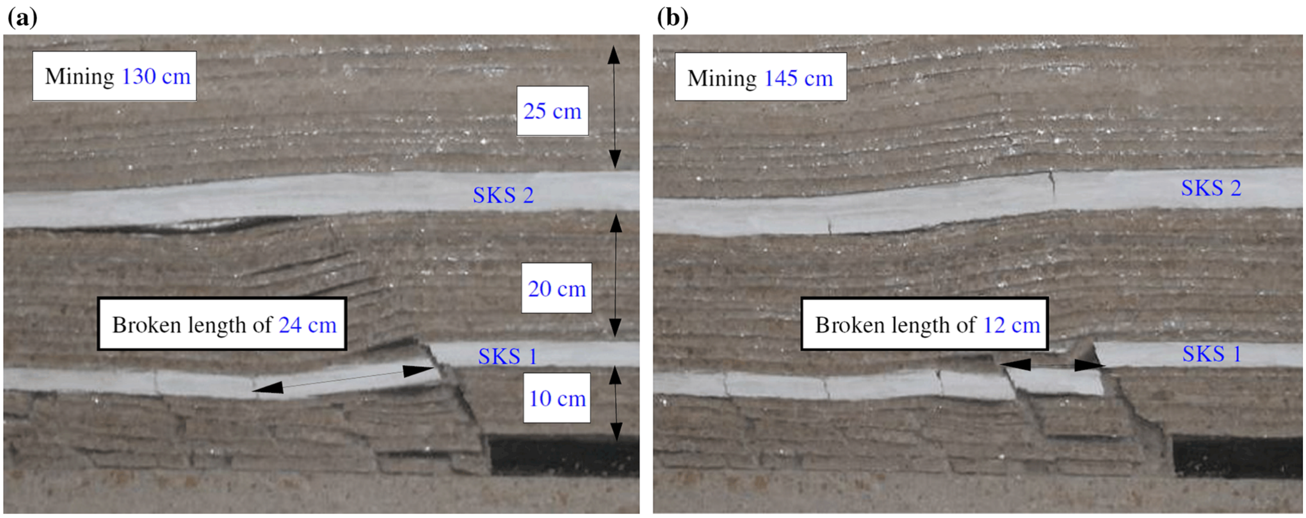


Fig. 9 Experimental results about the influence of SKS 2 on the break of SKS 1. **a** SKS 1 broke, SKS 2 bent and subsided and **b** SKS 1 broke in advance due to the break of SKS 2 (Ju and Xu 2013)

Conclusions

According to the observation results of the development of ground surface cracks induced by large-scale mining of coals with a shallow burial depth in a semi-desert aeolian sand area of western China, the law of development of static cracks in the peripheral area of the working face is similar to that under other geological and mining conditions; specifically, such static cracks take on an arc-shaped and grouped development mode. Due to the structure of the rock strata with a shallow burial depth and high intensity in the area, however, the crack angle is relatively large (specifically, larger than 80° at each observation point).

As compared with the existing research results, the dynamic crack above Working Face 12,406 of Bulianta Coalmine undergoes two cycles of generation, expansion to restoration, the developmental cycle is about 18 days, and the working face is advanced for about 220 m.

According to the structure and physic-mechanical properties of rock strata in the research area, this paper determined via theoretical analysis that the two expansion and development cycles of dynamic cracks are correlated with the periodic fracture of the compound key stratum in the structure of rock strata, and illustrated the correlation between the periodic fracture of the compound key stratum and secondary expansion and development of dynamic cracks. The results of theoretical calculation showed that the two development cycles of cracks coincide well with the interval of periodic roof breaking of the two key strata in the overlying rock stratum. In addition, this paper also simulated the secondary fracture of key strata via a similar material experiment.

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