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Similarity Simulation of Mining-Crack-Evolution Characteristics of Overburden Strata in Deep Coal Mining with Large Dip

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Abstract: Figuring out the mining-crack-evolution characteristics of overburden strata is very important to roof control, gas drainage, disaster prevention and high efficient mining. In order to obtain the mining-crack-evolution characteristics of overburden strata in deep coal mining with large dip, in this study, No.1221 coal mining face of Zhao coal mine is chosen as the research object to establish an in-house experiment system of similarity simulation. The experiments could measure the stress and displacement of overburden strata, which can provide useful information to investigate the mining-crack-evolution characteristics, displacement variations and movement characteristics of overburden strata associated the coal mining face. Experimental results show that with the advancing of coal mining face, the scope of gob increases gradually, and formation of the false roof of overburden strata basically reflects the evolution process of collapsing. The overburden strata weight is constantly transferred to the front and rear of coal mining face, which forms the supporting pressures on both sides of coal pillars, and causes the gangue’s collapsing in gob. The large dip of coal seam results in pressure disequilibrium in stress-increasing zone. Thus, the stress on the underside of gob becomes larger and larger, while the stress on upper side of gob decreases. The strata separation appears in the overburden strata of roof. Pressure-relief zone is mainly concentrated in the side of outlet roadway. Along the inclination direction of coal mining face, the crack development and strata separation are obvious, which create the passages for gas flow and migration. The similarity simulation results provide fundamental information for better understanding those mining-crack-evolution characteristics of overburden strata, which has become more and more important to control the roadway stability in coal mining and optimize the layout of gas drainage boreholes for improving.
Keywords: Similarity simulation; Deep coal seam; Coal mining face; Overburden strata; Mining-crack-evolution characteristics

1. Introduction

More than 95% of the coal mines are underground in China, underground coal seam mining always results in the overburden strata collapsing, even surface subsidence, the development of the overburden strata and coal seams above gob directly affects the mining safety of coal mining face. With the increasing demand of coal, the shallow coal resources are gradually reduced and depleted, thus the mining is getting deeper and deeper. Additionally, the high-intensity mechanized mining and intensive coal production also increase the threat of disasters in mining process. At the same time, many coal mining countries must face the problem of deep mining in the future, especially China. With the increase in the mining depth, there are many problems to be addressed in the mining process, such as the increasing mine pressure and ground temperature, increasing difficulty of roadway maintenance and exploration, deterioration of mining conditions, decreasing mining efficiency, etc. The maintenance of deep roadway has become the weakest part in coal mining system, the roadway maintenance depends on the roof stress and the mining crack development of surrounding rocks.

Many attempts have been made to better understand the breaking morphology of overburden strata, such as the subsidence, collapsing and the mining-crack-evolution process. Some theories and models to describe those complex processes are obtained (Kratzsch, 1983; Whittaker, et al. 1989, 1990; Peng, 1992). The breaking morphology of overburden strata is usually classified as "horizontal three areas" and "vertical three zones". The studies reported in literatures (Huang, et al. 2010; Yang, et al. 2012) showed that mining crack’s morphology in overburden strata changes with the advancing of coal mining face. Besides the typical classification of the breaking morphology above, Li has identified the "elliptical parabolic zone" of mining crack above gob (Li, 2000). Liu has proposed the concept of "roof annular fracture zone"(Liu, et al. 2004). Liu has applied similarity simulation to the
coal mining under remote protective seam and investigated the dynamic crack evolution law of overburden strata (Liu, et al. 2011). A protected coal seam deformation under mining of the remote protective seam has been studied using similar simulation test (Tu, et al. 2006), when the protective coal seam was mined out, the protected coal seam presented the "M" shape, forming symmetrical structure on both sides of coal mining face. Due to the pressure relief effect of protective coal seam mining, the relieved coal seams were in bending subsidence zone and the whole coal seam presents deformation and subsidence(Eva, et al.2012). As a result, the separation cracks in internal coal seam were well developed (Tu and Fu, 2012). Similarity simulation has been used to study the crack development characteristics of coal seam with thick aeolian sand in thin bedrock area during mining (Yang, 2014), the results from similarity simulation can provide a large amount of experimental information to describe the collapsing characteristics and migration law of overburden strata during mining and the pressure distribution law of the internal strata. Furthermore, the similarity simulation also has been used to study the influence of advancing length of coal mining face, speed and mining height on the height of the water flowing fractured zones, and the correlation of the advancing length and change rules of aquifer water levels and gob water inflow (Hang, et al. 2013). In addition, the fracture network, crack number and growth rate of porosity are greatly influenced by the control measures, such as hydraulic fracturing, hydraulic-controlled blasting, etc (Lin, et al. 2016; Ye, et al. 2017). With the increase in advancing length, the mining-induced cracks spread to the coal mining face dynamically and up into the roof (Abbas, 2012). Geological logs of the boreholes have recorded occurrence of four major consistent coal seams at different depths (Chatterjee and Pal, 2010), the results showed that vertical stress magnitude increases with depth, the gradient of vertical stress magnitude decreases within coal seams compared to the stress gradient at roof and floor of the same seams. Therefore, overburden strata pressure plays an important role in the crack evolution (Wei, et al. 2012). Similarity simulation can help to investigate those important phenomena, such as the falling failure features and movement law of the top overburden strata as well as the pressure distribution of internal strata (Li, et al. 2011). Similarity simulation shows that accompanied with the collapsing in
layer group, the overburden crack evolution is trapezoidal and the developing height of cracks discontinuously jumps, as the mining width increases. In collapsing zone, crack zone and bending subsidence zone, the development, propagation and closing of cracks were asynchronous and inner similarity (Wang, et al. 2015). The crack’s fractal dimension of overburden strata generally experiences two periodic change (i.e. small→ big→ small→ big) processes with the advancing of coal mining face (Zhou, et al. 2012). Cleats and fractures have been mapped from the coal exposures (Paul and Chatterjee, 2011), it was found that macro-cleat distribution is similar to that of well-developed coalbed methane basins. Change of orientation of cleat is related the orientation of fault systems and orientation of igneous intrusions occurring within the coal bearing packet. The displacement and stress distribution law of the overburden strata under initial breaking mining and periodic breaking mining were verified through the similarity simulation model, the displacement of coal mining face corresponded to the stress change at the measuring point and the formation of medium separated bed (Liao and Wang, 2013). A relationship between the length of mining-induced cracks and advancing lengths of coal mining face was investigated, the breaking of main key strata resulted in the closing of some cracks in the center of gob and the generation of new cracks (Liu, et al. 2016). The results of transient pulse test also showed that both mechanical and hydraulic apertures decrease at a decreasing rate with the increase in confining pressure (Zhao, et al. 2017). Mining methods also affect the mining-crack-evolution characteristics of overburden strata, insecure factors of FMM (fully-mechanized mining) of top coal in “three soft” coal mining face with large dip, which seriously affected the normal mining, were studied (Yang, et al. 2011), including rib spalling, roof collapsing and equipment slippage, etc. As a result, a set of FMM technology for complex and difficult seams (such as steeply inclined seams, soft coal seams with large dip), the mechanized filling mining technology and associated equipments have been developed (Wang, et al. 2014). In addition, numerical simulation has been conducted, e.g. using ANSYS software, to investigate the displacement variation, stress and strain of overburden strata and coal seams above coal mining face with large dip.
and mining depth. The numerical simulation results show that with the advancing of coal mining face, the crack development of overburden strata and coal seams becomes larger and larger, the gob area gradually expands, and the transverse stress of overburden strata and coal seams also expands (Ye, et al. 2017). Effect characteristic of coal seam and surrounding rock with large dip on bracing system becomes more obvious with the increase in dip. Therefore, it is necessary to consider the coal mining resistance and pay attention to its stability control during the design and the arrangement of the entire hydraulic bracing system. There is displacement difference between roof and floor of coal mining face with large dip, improving the stability of single bracing not only need to strengthen the bracing itself, but also need to adjust and control the displacement difference existing in the roof and floor. While considerable efforts with similarity simulation have been made to study the stress, displacement and collapsing of the overburden strata in recent years (Lu, et al. 2016; Hu, et al. 2016; Ghabraie, et al. 2015a, 2015b; Dai, et al. 2013; Huang, et al. 2011; Li, et al. 2011; Alejano, et al 1999; Hiramatsu, et al, 1979; Ren, et al. 1987), the mining-crack-evolution characteristics and subsidence law of the overburden strata of the inclined coal mining face has not yet been fully understood as it is quite different from the horizontal coal mining face, especially in deep coal mining with large dip.

As discussed above, the mechanical properties of coal and rock mass, and the distribution and structure of mining-induced cracks have been investigated, and a lot of significant results have been obtained by similarity simulation. However, those results are not closely related to the distribution and evolution of the mining crack network of overburden strata above mining coal seam with large dip and mining depth. Because researches on the generation, development, and evolution of the mining crack network and the gas passage are critically important, this paper will present a systematic study of similarity simulation to address the current existing problems of coal mining seam with large dip and mining depth. The similarity simulation was carried out based on the geology of No.1221 coal mining face of Zhao coal mine in Hebei Province of China. The movement characteristic and mining-crack-evolution law for the overburden strata above coal mining seam with large dip and mining depth are comprehensively analysed. This builds a theoretical foundation for improving gas drainage efficiency,
2. Profiles of coal mining face

The No.1221 coal mining face is located at 12\textsuperscript{th} coal seam, with a depth of 1000-1050 m and the average depth of 1020 m. The dip from east to west gradually increases (24-35\degree), featured by the average angle of 28\degree; the strike angle is about 29\degree. The coal thickness ranges from 9.12 m to 14.27 m and the average thickness is 10.69 m. The distance from 12\textsuperscript{th} coal seam to the top overburden strata is 28-40 m and is 32 m on average. The geological structure in this coal mining face is complicated, as it is in steeply inclined transition region. There are many special characteristics, such as tectonic stress concentration, soft coal, fracture development, broken roof and easy collapsing. Especially in the vicinity of the fault seam, the appropriate technical safety measures should be taken during construction. The coal mining face is implemented by using FMM (fully mechanized mining) of top coal collapsing, and advancing (excavation) is arranged along the bottom of coal seam. The gas pressure and content in No.1221 coal mining face is 1.6 MPa and 11.73 m\textsuperscript{3}/t, respectively. The Outburst Level Dividing Method suggests that this coal mining face is prone to coal and gas outburst. The spontaneous combustion period is estimated at 6 - 8 months. Coal dust has explosion hazards, and the explosion index is 47.4\%.

3. Similarity simulation on the crack evolution of overburden strata

According to the actual geological data of No.1221 coal mining face of Zhao coal mine in Hebei Province, the similarity simulation system is setup in laboratory and the simulation experiment is performed by using similarity materials used in coal mining process. The evolution and displacement of crack field in the mining process are investigated.

3.1. Experimental design

3.1.1 Basic requirements for similar simulation experiment

(1) Similar condition
In accordance with the general physical phenomena requirements, the similar simulation experiment should meet similarity conditions: geometric similarity, movement similarity, stress similarity, dynamic similarity and external condition similarity (Li, 1987; Wang, 2011). All the similarity conditions are designed according to the actual mining situation of No.1221 coal mining face. The similar simulation experiments are selected as follows:

- The deformation characteristics of rock are equal. The rock destruction in the overburden strata is mostly caused by the tensile stress exceeding the unidirectional tensile strength of the rock, so the unidirectional tensile strength is taken as the main index in overburden strata, the unidirectional compressive strength is taken as the main index in mining coal seam and floor strata.

- The linear ratio. In this simulation experiment, the linear ratio $\alpha_l$ is 1/100.

- Density ratio. $\alpha_d = \gamma_m / \gamma_p$, $\gamma_m$ is Model material density, $\gamma_m = 1.5\,\text{g/cm}^3$; $\gamma_p$ is density of prototype rock. In this simulation experiment, density ratio $\alpha_d$ is 1/1.48.

- The strength ratio. $\alpha_s = \sigma_m / \sigma_r$, $\sigma_m$, $\sigma_r$ is the strength of the model material and the rock, respectively. In this simulation experiment, the strength ratio $\alpha_s$ is 0.67/100.

- Time ratio. In this simulation experiment, time ratio $\alpha_t$ is 1/10. Namely, 1 hour is equivalent to 10 hours of actual mining.

- Displacement ratio. In this simulation experiment, displacement ratio $\alpha_w$ is 1/100.

(2) Similar material

- The selection of similar materials. Because the basic stress of deformation and failure of the surrounding rock is tension and pressure, the form of failure is shear and tensile, the deformation and failure of surrounding rock is related to its elastic modulus and Poisson's ratio. Therefore, materials are selected according to the main similarity conditions, coal seam and strata. According to the
thickness and strength of coal seams and strata, gypsum, sand and coal are mainly selected as the similarity materials in simulation experiment; the mica is selected as a weak surface of stratification in process of model layout, and the calcium carbonate and plaster are selected as cement. The strength and type of simulation materials can be adjusted by controlling quantity of calcium carbonate and plaster.

Material amount calculation. The amount of material per layer is calculated according to the follow formula.

\[ G = l \cdot b \cdot h \cdot \gamma_m \]

\( l \)-Total weight of model stratified material.
\( b \)-Model length.
\( h \)-Model width.
\( \gamma_m \)-Model stratified thickness.

Determination of material ratio. According to the selected similar materials, after many tests of mixture ratio, the ratio of similarity material is shown in table 1.

### Table.1. Ratio of similarity material in the model.

<table>
<thead>
<tr>
<th>No</th>
<th>Lithology</th>
<th>Thickness /m</th>
<th>Sand /kg</th>
<th>Plaster /kg</th>
<th>Calcium carbonate/kg</th>
<th>Coal powder/kg</th>
<th>Water /kg</th>
<th>Stratification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>top triangle</td>
<td>124.3</td>
<td>8.9</td>
<td>8.9</td>
<td>19.5</td>
<td>9 (without mica)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>sand shale</td>
<td>7.5</td>
<td>31.3</td>
<td>2.7</td>
<td>1.8</td>
<td>4.9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>powdered coal</td>
<td>9</td>
<td>42.1</td>
<td>3</td>
<td>3</td>
<td>6.6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>7th coal seam</td>
<td>3.7</td>
<td>18.8</td>
<td>1.3</td>
<td>1.3</td>
<td>2</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>sand shale</td>
<td>12.1</td>
<td>67.4</td>
<td>4.8</td>
<td>4.8</td>
<td>10.6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>sand stone</td>
<td>26.5</td>
<td>173.6</td>
<td>14.5</td>
<td>14.5</td>
<td>27.7</td>
<td>5 (without mica)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>9th coal seam</td>
<td>4</td>
<td>27.3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>shale</td>
<td>13.5</td>
<td>80.6</td>
<td>5.8</td>
<td>5.8</td>
<td>12.6</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>shale</td>
<td>7.5</td>
<td>41</td>
<td>3.4</td>
<td>3.4</td>
<td>6.6</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>11th coal seam</td>
<td>0.8</td>
<td>4.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>shale</td>
<td>18.7</td>
<td>88.1</td>
<td>6.3</td>
<td>6.3</td>
<td>13.8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>12th coal seam</td>
<td>10</td>
<td>38.2</td>
<td>2.7</td>
<td>2.7</td>
<td>4</td>
<td>6.8</td>
<td>3 (without mica)</td>
</tr>
<tr>
<td>13</td>
<td>sand shale</td>
<td>10</td>
<td>32</td>
<td>1.8</td>
<td>1.8</td>
<td>5</td>
<td>3 (without mica)</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>bottom triangle</td>
<td>66.6</td>
<td>3.8</td>
<td>3.8</td>
<td></td>
<td>10.4</td>
<td>5 (without mica)</td>
<td></td>
</tr>
</tbody>
</table>

3.1.2 Simulation test process

(1) Facture of Model
A similarity model is designed according to the coal-rock comprehensive histogram of No.1221 coal mining face of Zhao coal mine. Experiment is performed by plane stress platform with length, width and height at 2.5 m, 1.2 m and 0.2 m, respectively. The amount of each material is calculated according to table 1, after the materials are weighed well, the materials of each layer are added in the blender and mixed well. After each mixing, the materials in the blender are cleaned out and laid on a similar simulation platform. When the materials are laid, each molding thickness should be laid in strict accordance with the design thickness. Mica powder is evenly sprinkled after compaction. After laid, the model is placed 2-3 days. When the materials have basic hardness, the pressurized water bag begins to be preformed and then the model should be dry 10 days. After the similarity materials are dry, the front and rear plates are dismantled, then the grids are divided to observe mining-crack-evolution of overburden strata, as shown in Fig.1.

(2) Loading method

The top strata weight is evenly loaded by the pressurized water bag, which is shown in Fig.1. The pressurized water bag is located in pressure trough above the model. On both sides of the model, the water pipe of adjustable pressure is connected with pressurized water bag, which can adjust water pressure according to the required stress.

(3) Simulation of the mining process

According to the theoretical calculation and practical experience, it can be seen that the pillar at both sides of the model platform has a great influence on coal mining. According to the actual mining activities in No.1221 coal mining face, the coal pillars with length of 35 cm and 40 cm in both sides of the model are reserved to eliminate the border influence. The extraction length of model is 1 m. The excavation starts from the left, the coal mining face is pushed forward 10 cm of each time, i.e. the length of a small grid. The excavation is performed in strict accordance with similar parameters. The model panorama before coal excavation is shown in Fig. 1.

(4) Test instrument and point layout
According to displacement difference of overburden strata in the mining process, the horizontal and vertical lines are drawn on the front of dried model, the spacing between the horizontal line and vertical line is 10 cm, which is shown in Fig. 1. In order to obtain the stress change of overburden strata, miniature pressure cells are used to monitor vertical stress of the overburden strata, which are buried in the middle of overburden strata with distance of 10 cm and 25 cm from coal seam. Miniature pressure cells of resistance strain are selected to measure the stress distribution, the displacement detectors of resistance type of YHD-50 are selected to measure overburden strata movement, which are shown in Fig.2 and Fig.3.

Fig.1. Similarity simulation model panorama before coal excavation
Note: Red points present pressure cells, green points present displacement detectors.

Fig. 2. Design diagram of the pressure cells and displacement detectors.

Fig. 3. Installation diagram of the displacement detectors.

3.2. Similarity simulation and results analysis

Movement characteristics and displacement of overburden strata are simulated in this model, the simulation process and results are as follows.
3.2.1 Movement characteristics of overburden strata

According to the time ratio, the mining is circular from left to right. Overall length of the model is 100 cm, which is equivalent to 100 m in the length of prototype of coal mining face. To facilitate understanding, the phenomena of similarity mining are described based on the prototype. With the advancing of coal mining face, the collapsing process of overburden strata and coal seam is shown in Fig. 4.
Fig. 4e. Advancing distance is 50 m

Fig. 4f. Advancing distance is 60 m

Fig. 4g. Advancing distance is 70 m

Fig. 4h. Advancing distance is 80 m

Fig. 4i. Advancing distance is 85 m

Fig. 4j. Advancing distance is 90 m
In Fig. 4, with mining development, the scope of gob gradually expands, and the false roof of overburden strata basically presents the characteristic of collapsing following mining activities. For the immediate roof, when the advancing distance is 0 - 50 m, the separation cracks of overburden strata gradually develop from bottom to top, and cracks in faults are also accompanied by obvious changes. When the advancing distance is 20 m, overburden strata generate the clear separation cracks, and the separation height is about 10 m on the top of the roof, but cracks in faults are not obvious. When the advancing distance is 35 m, separation changes in roof become more obvious, a lot of separation cracks can be observed, and maximum separation height reaches about 20 m on the top of the roof, which is near to 11th coal seam. At this time, cracks in faults are located above the excavation point of inlet roadway, which are obvious. When the advancing distance is 40 m, overburden strata and top coals firstly produce collapsing, the collapsing height is about 4 m. At this time, the separation in roof continues to develop and a lot of cracks in faults are generated in overburden strata, crack height in faults is about 10 m. When the advancing distance is 50 m, the first weighting appears, collapsing height is 18 m, and the maximum height of separation cracks of overburden strata is 35 m from the coal seam. With the advancing of coal mining face, the stratified collapsing appears in immediate roof. Each advancing of 10 - 20 m, there is a collapsing, the maximum collapsing height is 25 m. Therefore, the collapsing step distance of roof is about 10 - 20 m. The numerical simulation results in literature (Ye, et al. 2017) showed the similar results, namely, with the advancing of coal
mining face, the crack development of overburden strata and coal seams becomes larger and larger, the gob area gradually expands, and the transverse stress of overburden strata and coal seams also expands.

3.2.2 Overburden strata displacement

(1) Analysis on the movement law of overburden strata

In order to facilitate the analysis, the curves of displacement measured by displacement detectors installed in same vertical line and the advancing distance of coal mining face are plotted in one coordinate system (the horizontal coordinate is the advancing distance (unit: m), while the longitudinal coordinate is the roof subsidence (unit: mm)). The displacement curves measured by the detectors (①②③, ④⑤⑥, ⑦⑧⑨, ⑩⑪⑫) are illustrated in Figs. 5-8, respectively.

Displacement detectors of ①, ② and ③ are installed on the top of reserved coal pillar in the excavation side of inlet roadway, whose relative place is shown in Fig. 2. With the continuous advancing of the coal mining face, the overburden strata experience tensile deformation and compression deformation. Under the effect of collapsing and bending subsidence of overburden strata, the tensile stress is gradually transmitted to the measuring point, and cracks in the measuring points begin to appear and gradually develop. With the increase in collapsing height and the upward...
development of bending subsidence, the cracks gradually develop from bottom to top. The measured
displacement presents a slow increase by approximate straight line, the increase is very small and slow
before cracks obtain the full development. In Fig. 5, when the advancing distance is more than 50 m,
the farther the distance from the roof is, the larger the subsidence of displacement detector is, the
subsidence difference also increases, which show that the strata under the displacement detector
experiences larger pressure. During the experiment, when the advancing distance is 50 m, the first
weighting appears, and the collapsing height is 18 m.

Displacement detectors of ④, ⑤ and ⑥ are installed in the same vertical line with distance of
20 m from excavation side in inlet roadway. When the advancing distance of coal mining face is 0 - 30
m, displacement change is relatively flat, the cracks are still in the process of instability and initiation,
most of which are separation cracks. When the advancing distance is 35 m, the separation in roof
increases and become more obvious. The maximum height of the separation in roof is about 20 m
from the coal seam, which is near to 11\textsuperscript{th} coal seam. When the advancing distance is 40 m, the first
collapsing appears in the overburden strata and top coals, collapsing height is about 4 m. When the
advancing distance is 50 m, the first weighting appears, collapsing height is 18 m, and the height of
separation cracks of overburden strata is 35 m from the coal seam top. At this time, 11\textsuperscript{th} coal seam
produces obvious bending subsidence. When the advancing distance is 70 m, 11\textsuperscript{th} coal seam begins to
collapse, the displacement detector of ④ subsides with the coal seam of collapsing, the displacement
variation takes on the sharp increase. With the local collapsing of 11\textsuperscript{th} coal seam, the separation cracks
constantly increase and develop upward, the maximum height of separation cracks of overburden
strata is about 40 m from the coal seam. During the advancing distance from 70 m to 100 m, the
bending subsidence and the displacement constantly increase, as shown in Fig. 6.
Displacement detectors of ⑦, ⑧ and ⑨ are installed on the same vertical line with distance of 50 m from excavation side in inlet roadway. When the advancing distance of coal mining face is 0 - 20 m, there is basically no change of the monitored displacement. When the advancing distance is about 20 m, the overburden strata begin to produce separation cracks, the displacement also begins to gradually increase, which indicates that the influence of mining in front of 30 m on cracks is more obvious. When the advancing distance is 40 m, the measured displacement velocity at the first collapsing place increases. When the advancing distance is 50 m, the first weighting appears, collapsing height is 18 m, and the maximum height of separation cracks of overburden strata is 35 m from the top of coal seam. During the advancing distance from 80 m to 90 m, displacement change takes on the sudden jump, the collapsing height is about 20 m, as shown in Fig.7.
Displacement detectors of ⑩, ⑪ and ⑫ are installed on the same vertical line with distance of 90 m from excavation side in inlet roadway. The advancing distance of coal mining face is less than 55 - 60 m, where there is basically no displacement change. When the advancing distance is 60 m, three displacement measuring points present obviously different changes. With the advancing of coal mining face, the influence of mining in front of 30 m on cracks becomes more obvious. When the advancing distance is 100 m, after the collapsing stability of overburden strata, it is found that collapsing angles in the inlet and outlet roadway are not symmetric, and the difference of these angles is large. The collapsing angle near to inlet roadway is about 90°, which is almost parallel to the vertical direction. But the collapsing angle near to outlet roadway is about 45°. Therefore, along the coal seam inclination direction, the subsidence of overburden strata in the mining field is characterized by obvious asymmetry, and the maximum subsidence is biased in favor of down-roadway side of the mining area, as shown in Fig.8.

During the experiment, it has been found that a big crack goes through 9th coal seam from roof in up-roadway side of gob in inclination direction, when the coal seam is mined, as shown in Fig.4l. After analysis, it is found that the crack is caused by the strata slippage. Due to the coal seam inclination, the rocks in the upper part of gob may fall, fill and compact the lower part of gob under...
the action of gravity, which increases the space of the upper part of gob and reduces the space of the lower part of gob. Therefore, the upper strata above gob displaces sharply, while the lower strata above gob displaces slightly.

Fig. 8. Displacement curves in measuring points of ⑩, ⑪ and ⑫

Fig. 9. Horizontal displacement curves

In Fig. 9, overburden strata not only produce the bending subsidence of vertical direction, but also cause the movement along the coal seam inclination direction. When the advancing distance is 40 m, overburden strata and top coals begin to collapse. With mining of the coal seam, the displacement of overburden strata along the coal seam inclination direction increases constantly. Strata slippage along the coal seam inclination direction results in that part of strata near to down-roadway side are compact and another part of strata near to up-roadway side are stretched, even cut off. When the
advancing distance is 70 m, displacement variation sharply increases and the slope of the curve
suddenly becomes larger. Due to the coal seam inclination, the rocks in the upper part of gob may fall,
also produce slippage toward down-roadway side along the floor under the action of gravity.

(2) Analysis on stress distribution of surrounding rock

In the mining process, the coals are mined out, coal seam roof produces successively bottom-up
falling, separation, bending subsidence, which changes the stress state in mining field and produces
stress redistribution of the surrounding rock. In the similarity experiment model, 4 pressure cells are
installed in 11th coal seam, as shown in Fig. 2. In order to conveniently analyze the stress distribution,
the relative distance from the mining point in coal seam is chosen as the horizontal coordinate, and the
pressure variation is taken as the vertical coordinate, which is shown in Figs.10-13.

![Stress variation curve of the measuring point I](image-url)
In Figs. 10-13, the pressures in the measuring point I and II constantly increase with the mining.
activities. With the advancing of coal mining face, the scope of gob becomes larger and larger, the overburden strata weight is constantly transferred to the front and rear of coal mining face. As a result, both sides of coal pillars and gangues are collapsed in gob, forming the supporting pressure. Therefore, the stress concentration zone and pressure-relief zone are formed in a certain range. With the advancing of the coal mining face, the mining point is getting closer to the measuring point II and III, the stress of each measuring point increases with the advancing of the mining. A peak appears before the mining near to the bottom of each measuring point, at a distance of about 5 m in the vicinity of the mining point in coal seam. The peak’s effect scope is about 5 - 25 m in front of mining point, resulting in the stress concentration in coal seam and strata of 5 -25 m in front of mining point, and the stress concentration is further constantly pushed forward with the mining.

When the coal seam continues to be mined, the stress increases constantly, the closer the mining moves to the measuring point, the larger the stress is. In the distance of 5 m from measuring point, tension and compression in overburden strata along the coal seam direction causes strata deformation and fracture, hence, the stress of coal body decreases sharply. When mining is in the distance of 10 - 20 m from measuring point, the stress decreases further and then drops to negative value. Within this range, the strata generate tension and compression along the coal seam inclination direction, the pressure begins to decrease, the downward bending extent reaches maximum. Thereafter, because the coal body in front of coal mining face has experienced the elastic-plastic deformation, the coal body is completely in plastic state. At the same time, the three-directional pressure state is gradually transformed into a one-directional pressure state. Thus coal body’s supporting capacity decreases sharply, as well as the stress value decreases sharply. Then, the pressure curve changes slowly. In this case, a larger range of pressure formed in gob at the rear of the measuring point is unloaded, forming a pressure-relief zone.

After the mining, the strata gradually become stable. According to the movement and deformation characteristics and the stress distribution of strata, the cracks are evolving in the overburden strata in both the vertical and the horizontal directions along the inclination direction of
coal mining face, as shown in Fig. 14. Crack distribution of overburden strata in vertical direction is featured by a collapsing zone located above the coal seam with the height of about 25 m, and a crack zone upper about 70 m. In other words, the scope up to 25 m in overburden strata is the collapsing zone, the crack zone spans from 25 m to 70 m, and above 70 m is the bending subsidence zone. The crack height is about 10 times of mining height. Therefore, 11\textsuperscript{th} coal seam is corresponding to the collapsing zone, 9\textsuperscript{th} coal seam is in the crack zone and 7\textsuperscript{th} coal seam is in the bending subsidence zone.

Crack distribution of overburden strata in horizontal direction is described as follows. Along the inclination direction, the overburden strata and 11\textsuperscript{th} coal seam up to 5 m in front of coal mining face belong to a bending subsidence zone, followed by a rock supporting pressure zone from 5 m to 25 m in front of coal mining face, and then belong to bending subsidence zone again in scope of 20 m in rear of coal mining face. The overburden strata and 11\textsuperscript{th} coal seam beyond scope of 20 m in rear of coal mining face belong to pressure-relief zone. Due to coal seam inclination, the movement of strata near to up-roadway side in gob increases sharply, and the development of cracks in this zone is the most sufficient. In addition, there is a relatively large space in the vicinity of the collapsing line. The numerical simulation results in literature (Ye, et al. 2017) also showed that large dip of coal seam results in larger supporting pressure in underside of gob and litter supporting pressure in upper side of gob. Along the inclination direction of coal mining face, pressure relief zone is mainly concentrated in outlet roadway of coal mining face, the crack development and strata separation is obvious.
4. Conclusions

This study presents a similarity simulation experiment to investigate the crack development process of the overburden strata, stress distribution and evolution characteristics of the crack field in deep coal mining with large dip. Following results could be concluded.

(1) Mining effect can produce significant separation cracks and breaking cracks in overburden strata. Cracks are often located at the coal mining faces of both ends of gob, which takes on the trapezoidal distribution. The crack evolution in the overburden strata would go through a process of unloading, destabilization, cracking, the sudden opening and closing of cracks, crack keeping, the rapid re-closing of cracks and finally the complete closing of cracks by compaction. Cracks increase firstly and then decrease with separation. The crack evolution in overburden strata in both vertical and horizontal directions is observed along the inclination direction of the coal mining face.

(2) In the mining process of coal seam, the stress of overburden strata is dynamically developing. The coal body in front of coal mining face is completely in the plastic state as it has experienced the elastic-plastic deformation. As the three-directional pressure state is gradually transformed into one-directional pressure state, coal body’s supporting capacity decreases significantly, hence the stress decreases sharply.
(3) During coal mining, the movement of overburden strata leads to the suspension of the roof strata and transfers the partial weight to the surrounding rock mass. As a result, the stress redistributes within the surrounding rocks in gob and forms supporting pressure zone and unloading pressure zone. The supporting pressure zone is formed in the coal pillar of the mining boundary, the upper and lower strata. The increased pressure promotes the plasticity of the coal pillar, resulting in the supporting pressure zone moving away from gob.

(4) The dip of the coal seam may cause the pressure disequilibrium of the pressure- increase zone in both sides of gob. Supporting pressure in underside of gob is obviously larger than in the upper side of gob. This will form a reduced pressure zone in the roof and floor rock, and further cause the separation in roof strata.

(5) Due to the coal seam inclination, under the action of gravity, the rocks in the upper part of gob may fall, fill and compact the lower part of gob. This phenomenon increases the space of the upper part of gob and reduces the space of the lower part of gob. Therefore, the upper strata above gob displaces sharply, compared with the lower strata above gob, the displacement is relatively slow. Cracks of pressure-relief zone near to outlet roadway are more obvious than those near to inlet roadway, which promotes further strata separation. The pressure relief effect in the pressure-relief zone near to outlet roadway is also better than those in pressure-relief zone near to inlet roadway.

(6) With the advancing of mining, the main roof produces separation collapsing. In subsequent mining, a process of separating, cracking, collapsing and compacting will repeatedly occur in the roof strata. The collapsing step distance of roof is about 10 - 20 m and the maximum collapsing height is 25 m.

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References


Highlights

1. Similar simulation experiment model with large dip and mining depth is established.

2. Mining-crack-evolution, displacement variations characteristics are obtained.

3. Large dip of coal seam results in pressure disequilibrium in stress-increase zone.

4. Crack distribution after the collapsing of overburden strata is obtained.

5. Collapsing step distance of roof and the maximum collapsing height are obtained.

Thank you very much!