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Experimental investigation on mining-induced strain and failure characteristics of rock masses of mine floor

Wei Zenga, Zhen Huangab, Yun Wub, ShiJie Lia, Rui Zhangc and Kui Zhaoa

aSchool of Resources and Environment Engineering, Jiangxi University of Science and Technology, Ganzhou, China; bSchool of Earth Sciences and Engineering, Nanjing University, Nanjing, China; cKunming Survey, Design and Research Institute CO. LTD of CREEC, Kunming, China

ABSTRACT

Underground mining is known to cause the deformation and failure of the surrounding rocks and frequently associated with water-inrush through the mine floor. In this study, in-situ strain tests along with borehole imaging measurements were utilized to investigate the deformation and failure characteristics of the rock mass of the mine floor caused by mining. We directly measured the strain and borehole images of the rocks in the mine floor at different depths in five coal mines in the Yanzhou mining area, China. We observed from plotting the increments of strain that mining caused and then led to the deformation and failure of the rock mass of the mine floor. The zone in the floor that was affected by stress from mining was over 170 m in length and decreases with depth. We also found that the depth of failure in floor of the five different coal mines varied between 8.4 to 20 m.

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Coal mining; mine floor; rock failure; axial and radial strain; working face

1. Introduction

In recent years, coal mining has been conducted at increasingly greater depths. This has resulted in a higher risk of water-inrush into the mine through the mine floor, which is one of the greatest challenges that need to be addressed by the mining industry (Meng et al. 2012; Zhang et al. 2016; Ma et al. 2017, 2018, 2019; Slaker and Mohamed 2017). In the process of deep mining, the risk of water-inrush increases with high groundwater pressure and deep deposits (Chen et al. 2015; Huang et al. 2018). Therefore, it is important to accurately determine the depth of the deformation and failure (Herda 2011; Zhu and Wei 2011; Huang et al. 2014; Yin et al. 2016) in order to put forth timely measures to prevent the inrush of groundwater. The inrush of groundwater through the floor of the coal seam is part of the main contributors to major disasters in coal mines in China (Huang et al. 2019a; Wang et al. 2019). Thus, finding ways to avoid the inrush of water is an important technical problem in coal mining safety.
Mining causes stress changes in the rock mass, that is, loading and unloading during the advancement of mining, and stress redistribution in the rock mass (Konicek et al. 2013). Similarly, the evolution of cracking in rock masses also undergo a process which involves three stages: the first stage in which few cracking takes place, the second stage in which the cracks are gradually propagating, and finally, the third stage, where cracks rapidly propagate throughout the rock mass (Lu and Wang 2015). The cracks in the rock mass of the mine floor change due to mining induced stress changes, and the water resistance capacity is gradually reduced with the increase in mining depth and extraction, which lead to the inrush of water through the mine floor (Zhu et al. 2013, 2014). Therefore, we examined the deformation and failure characteristics of the rock mass of the mine floor during mining operations to prevent water-inrush through the mine floor based on in-situ tests carried out in the Yanzhou coal mine area, which is the main coal production area in Shandong Province, China (Zhu et al. 2013, 2016; Huang and Cheng 2017).

At present, the deformation and failure characteristics of the rock mass of the mine floor of seams have been studied by many both Chinese and international academics and practitioners, so a large volume of research results have been obtained (Li et al. 2013; 2015; Feng et al. 2016; Li et al. 2016; Zhu and Zhang 2018). As a result, many research methods for determining the characteristics of failure of the mine floor have been proposed, which can be primarily grouped into field measurements (Zhang et al. 2006; Kang et al. 2010; Xu et al. 2012; Huang et al. 2014, 2018; Li et al. 2014; Yin et al. 2016; Zhao et al. 2016), laboratory experiments (Li et al. 2014; Liu et al. 2015; 2017; Sun et al. 2017; Zhu et al. 2017; Liu et al. 2019) and analytical calculations (Wang et al. 2009; Yu et al. 2009; Song et al. 2016; Yin et al. 2016; Cheng et al. 2018; Su and Wei 2018; Liu et al. 2019).

However, compared to laboratory experiments and analytical calculations, in-situ tests are more reliable and effective method to determine the characteristics of the failure of the mine floor and the depth of failure of the floor of the coal seam and which have been widely used to examine many coal mines (Kang et al. 2010; Li et al. 2014; Zhao et al. 2016; Liu et al. 2017; Wang et al. 2017; Meng et al. 2019). At present, there are many field measurement methods to determine the properties of the floor of the coal seam including: water injection tests (Huang et al. 2014, 2018; Yin et al. 2016; Huang, Li, et al. 2019) in which boreholes are drilled, with some that serve as the water injection holes while the orifice of others are sealed with a flange. Water is subsequently injected into the boreholes that are not sealed off before mining and after the completion of mining to understand how much damage this would cause to the rock mass of the mine floor and the depth of the damage to the floor of the coal seam by comparing the amount of seepage in each section. Another field measurement method is the electric current computed tomography (Zhang et al. 2006; Xu et al. 2012) which is used to examine the failure characteristics of the floor and determine the depth of failure by measuring the differences in the electric resistivity of the rock of the mine floor before, during and after mining. Then there is microseismic monitoring (Jian et al. 2011; Zheng et al. 2012; Cheng et al. 2017) which is used to determine deformation and range of the failure as well as the shape of the rock mass of the mine floor by recording the microseismic signals from the rock mass.
In this study, we carried out a case study of the floor of typical working faces in the Yanzhou coal mine area and the characteristics of the failure zone by carrying out in-situ strain measurements and using an optical televiewer (an ultrasonic imaging tool), which can effectively prevent the disadvantages of carrying out a single test that can only determine the scope of the failure based on the degree of deformation of the mine floor with depth and in different directions. In-situ strain measurements are used for the ongoing monitoring of deformation on the mine floor and structural changes with strain gauges placed at different depths of the mine floor. Based on the measurements from the strain gauges placed at different depths, not only can we determine the distance from the pressure induced by mining before water inrush occurs and the influence of the pressure concentration during the advancement of the mine, but can also be used to calculate the differences in the vertical deformation of the mine floor, thus determining the range of the depth of failure. An optical televiewer which is an ultrasonic imaging tool is placed in the mine floor to visualize and obtain images of the structure of the rock strata of the borehole wall with a probe. Moreover, the optical televiewer also can verify the extent of the influence of mining on the mine floor based on changes in the structure of the rock strata before and after the borehole wall has been damaged.

2. Experimental

2.1. Procedures and method

We used a strain gauge to obtain the strain in the floor. The schematic representation of the strain gauge is shown in Figure 1. The strain induced signals produced from the gauge were connected to a KBJ-12 data logger which recorded the data. The figure shows that the strain gauges used in this study provide two types of strain measurements: axial and radial strain measurements. The output signals from the axial strain gauge correspond to channels 1, 3, 5, and 7, those from the radial strain gauge correspond to channels 2, 4, 6 and 8. In the strain test set-up, channels 1 and 5; 2 and 6; 3 and 7; and 4 and 8, are all symmetrical. With the advancement of the working face, the rock mass of the mine floor experienced a series of deformations, and the degree and distribution of deformation can be measured by installing a series of strain gauges at different depths in the boreholes, which were placed throughout different areas of the mine floor.

Borehole imaging was carried out by using a YTJ20 borehole camera system (Huatai Science and Technology Development Co., Ltd.). The system has a high-resolution camera that can capture color images. The camera is used to view the structure of the internal walls of the borehole at different depths and the captured images are displayed on an LCD screen in real time, including the overall situation of the borehole wall, the width of the separation of the rock mass, amount of fracturing in the rock mass and the fractured rock mass itself.

2.2. Application at Baodian coal mine

Taking the site conditions and technical requirements into consideration, five mines (Baodian, Dongtan, Zhaolou, Yangcun and Xinglongzhuang) were examined to
calculate the deformation and failure of the floor during mining. The basic strata information of the five mines is provided in Table 1.

The Baodian coal mine is used here as an example. This coal mine is found in the center of the Yanzhou mining area, as shown in Figure 2. The deep coal seam has the characteristics of a stable layer and simple structure as it contains a semi-bright coal, and the average thickness is 8.6 m. The overlying layer is Quaternary mudstone with an average thickness of 4.3 m. The floor is argillaceous siltstone and fine sandstone with an average thickness of 2.5 m and 16.6 m, respectively with intercalation of thin layers of muddy siltstone. Therefore, the in-situ strain measurement and imaging of the mine floor at the No.5304-2 working face are carried out, and three test boreholes were drilled. The specific parameters are shown in Table 2.

Boreholes 1 and 2 were used to set up the strain gauges. The four gauges inserted into Borehole 1 are located 10 m, 14 m, 16 m and 19 m from the coal seam and the three gauges inserted into Borehole 2 are 12 m, 15 m and 17 m from the coal seam. In this way, the placement of the seven strain gauges in the two boreholes to measure both the horizontal and vertical strains can better reflect the deformation of the rock strata at 10-19 m below the mine floor. Borehole 3 is used for observation. The degree of damage is determined by a comparison of the rock strata before mining and after the completion of mining with advancement of the working face. Figure 3 is a diagram of the borehole measurements.

Testing was successfully done for a typical working face in the Baodian Mine based on the design parameters. The strain induced values are obtained at all seven measured points, and full images are also obtained from borehole imaging. The strain measurements started when the testing point was 45 m before the working face, and ended when the testing point was 60 m behind the working face. They are influenced...
| Parameter       | Baodian Coal Mine | Dongtan Coal Mine | Zhaolu Coal Mine | Yangcun Coal Mine | Xinglongzhuang Coal Mine |
|-----------------|-------------------|-------------------|------------------|-------------------|-------------------------|
| Name of coal seam | No.3 coal seam    | No.3 coal seam    | No.3 coal seam   | No.16 coal seam   | No.3 coal seam          |
| Depth of seam (m) | 256.3 ~ 357.3     | 556.38 ~ 640.34   | 962.5 ~ 1006.5   | 241.89 ~ 315.84   | 3375 ~ 496.8            |
| Thickness of seam (m) | 8.30 ~ 8.80      | 8.10 ~ 9.45       | 0 ~ 8.1          | 0.8 ~ 1.5         | 6.20 ~ 10.4             |
| Dip of seam (°)     | 6 ~ 15            | 0 ~ 12            | 0 ~ 12           | 1 ~ 18            | 1 ~ 18                  |
| Roof of seam       | The main roof has interbedded medium-fine sandstone with an average thickness of 23.21 m, while the direct roof is mudstone with an average thickness of 4.26 m. | The main roof is medium and fine sandstone with an average thickness of 20.18 m, while the direct roof is siltstone with an average thickness of 3.20 m. | The main roof is interbedded medium-fine sandstone with an average thickness of 10.33 m, while the direct roof is mostly siltstone with an average thickness of 6.4 m. | The direct roof is the lower limestone aquifer of the No.10 coal seam with an average thickness of 5.25 m. | The main roof is interbedded medium-fine sandstone with an average thickness of 20.34 m, while the direct roof is fine sandstone with an average thickness of 11.50 m. |
| Floor of seam       | The direct bottom is siltstone with an average thickness of 2.45 m, while the previous bottom is interbedded siltstone-fine sandstone with an average thickness of 16.64 m. | The direct bottom is mainly siltstone with an average thickness of 4.04 m, while the previous bottom is medium and fine sandstone with an average thickness of 12.78 m. | The direct bottom is mudstone with an average thickness of 1.0 m, while the previous bottom is silt-fine sandstone interbedded with an average thickness of 5.61 m. | The direct bottom is aluminous mudstone or mudstone with an average thickness of 2.14 m, while the old bottom is siltstone with an average thickness of 7.04 m. | The direct bottom is siltstone with an average thickness of 2.14 m, while the old bottom is siltstone with an average thickness of 7.04 m. |
by the same pressure source, and in order to reduce errors, we used the average measurements of two symmetrical channels in the data processing. Due to the large amount of data and space limitations, this paper only focuses on changes in the average strain of the axial gauge (3 and 7) and radial gauge (2 and 6). That is, an analysis and evaluation will be done only on the plotted curves of these four gauges. The changes in the monitored data by the strain gauges at different depths of the failure zone during excavation and advancement are examined.

The relationship between the strain increment and the advancement of the working face as determined by the seven strain gauges at different borehole depths is shown in Figures 4 and 5. From the changes in the strain variation, it is obvious that the deformation of the rock at 10-19 m below the mine floor showed a pressure concentration during the advancement of mining and unloading of the pressure when mining was completed. At a distance of 60 m from the measurement points, the strain changed at varying degrees at the tested points at different depths and there were no measurable strains until the working face was about 50 m from the measurement point. The induced strain is larger at shallower depths as opposed to the measured points that show larger strain at greater depths. This shows that there is a gradual

![Schematic diagram of Yanzhou mining area.](image)

**Figure 2.** Schematic diagram of Yanzhou mining area.

**Table 2.** Design parameters of borehole recording.

| Technical Parameters                             | Borehole 1 | Borehole 2 | Borehole 3 |
|-------------------------------------------------|------------|------------|------------|
| Diameter of borehole (mm)                       | 91         | 91         | 91         |
| Angle between horizontal and borehole directions (°) | 30 (Angle of depression) | 70 (Angle of elevation) | 90 (Angle of elevation) |
| Depth of borehole (m)                           | 10         | 6          | 13         |
reduction in the induced strain with increasing depth. The magnitude of the induced strains at depths of 10 m and 12 m is relatively low at 30 to 65 m from the working face, but they rapidly increase starting at 30 m from the working face. The maximum induced strain reaches about 6000 \( \mu \varepsilon \). Among the strain gauges, the strain gauge

Figure 3. Diagram of borehole measurements.

Figure 4. Average change in strain measured by axial strain gauges (3 and 7) during mining.
installed at a depth of 10 m was lost due to mining when the working face reached about 8 m from the strain gauge location. Therefore, the strain gauge installed at a depth of 12 m can only record data from a distance of 65 m before mining takes place to 50 m after mining. However, the amount of the strains at depths of 14 m, 15 m, 16 m, 17 m and 19 m is obviously less than that at depths of 10 m and 12 m. The maximum amount of induced strain is only about 3000 με. More data collected for the entire measurement section show similar characteristics.

In comparing the axial and radial strain signals from the strain gauges installed at shallower depths of 10 m and 14 m, it can be found that the amplitude of the radial strain is significantly higher than that of the axial strain. The maximum radial strain measured at a depth of 10 m at the bottom from the borehole is about 6000 με, and that by the axial strain is only about 3500 με. However, the amount of axial strain is higher than the radial strain at a depth of 12 m.

Figure 6 shows the plotted maximum axial and radial strains with depth. It can be observed that they gradually decrease with increase in depth, and the range of the changes in the strain is greater at depths of 12 m or more, while there is less change in the strain at depths of 12 m or less.
The observation provided information on the structure of the surrounding rocks at different depths of 46 m, 23 m ahead of the borehole, and 2 m and 17 m through the borehole. Selected images of the boreholes at depths of 4.8-5.3 m, 7.4-7.9 m, 10.7-11.2 m and 12.7-13.2 m are shown in Figure 7.

During the advancement of the working face, no obvious deformation was measured in the surrounding rock in the measured borehole at all depths except when the rock appeared to undergo obvious deformation at a depth of 10.7 m with the advancement of the working face to 46 m from the borehole. This indicates that the mine floor with the borehole has not been affected by the pressure of loading.
prior to mining. With the advancement of the working face to 23 m, cracking of the bedding layer and deformation of the surrounding rock at a depth of 4.8 m were initiated. There was some plastic deformation at a depth of 7.4 m, and the rock mass at a depth of 10.7 m was severely damaged. However, there were no signs of deformation due to the plastic deformation of the surrounding rock at a depth of 12.7 m, which indicates that the depth of the disturbance from mining is approximately limited to 10 m. With advancement of the working face to more than 2 m from the borehole, the surrounding rock at depths of 4.8 m and 7.4 m appeared to have slight plastic deformation. The number of crack openings in the rock mass at 10.7 m obviously increased, while there was almost no deformation due to disturbance from mining at 12.7 m. With advancements in the working face beyond 17 m from the borehole, the rock mass at a depth of 4.8 m was severely damaged, and cracking of the bedding occurred at a depth of 7.4 m, while the degree of damage at 10.7 m was further increased. There was no observable damage due to the disturbance at a depth of 12.7 m, which indicates that the measured borehole is not affected by the mining disturbance.

The borehole images of the surrounding rock structure at a depth of 46 m, 23 m in advance of the borehole and 2 m and 17 m through the borehole were compared and analyzed. It was found that severe damage caused by mining disturbance is confined to a sag depth of 10.7 m, and the surrounding rock at a sag depth of 12.7 m shows signs of disturbance, but the amount of disturbance is minimal. The measurements of the induced strains and observations from the borehole images also showed that the depth of failure of the mine floor of the Baodian Mine is approximately at a depth of about 10 m to 12 m, and the mining pressure is constant.

3. Discussion

The measured deformation and failure of the mine floor of five typical working faces in five mines in the Yanzhou mining area provide valuable information on the effects of mining on the mine floor. Based on the observed pressure regimes and rock mechanic theory, this paper provides a detailed analysis on the mining induced pressure on the rock mass and characteristics of the different zones of the mine floor, the stress state of the mine floor with mining activity, the failure characteristics and the depth of failure of the mine floor. Conclusions are then provided based on field observations and analyses.

3.1. Mining-induced characteristics of stress on mine floor

Zhu et al. (2017) stated that with the pressure caused by mining, the abutment pressure from the mining in front of and behind the working face can be divided into four areas where there are no changes in the stresses in the rocks; an increase in stress; a decrease in stress; and stress changes are a constant. With further distance away from the testing area where there are no changes in stress due to mining, the vertical stresses are equal to the self-weight of the material. The area with an increase in stress is due to the influence of the goaf, as the pressure of the roof is concentrated
in the load bearing area of the front pillar. Due to the unloading of the pressure in the goaf, the roof initially collapses and the overlying rock mass moves slightly to the area with reduced stress behind the mined face. However, this does not transfer all of the stresses in the rock to the caved material, so that the stresses from the caved material on the floor is less than the overburden pressure. With continuous compaction of the caved material, the stresses gradually stabilize and become constant. It is generally believed that the loading intensity in this area is close to the overburden pressure.

The sensors operated normally during the entire observation process, so the strains were recorded continuously from all of the measured points. Based on the above analysis, we obtained the strains with distance during the advancement of mining and after the completion of mining, along with the strains in the zones of each working face with a high amount of straining. The information was collected from the five mines of interest, which are summarized in Table 3. There are parts of the table with no data which is partly due to the failure of the strain gauges due to pressure induced by mining and human error.

| Table 3. Table of summary of strains with distance. |
|---------------------------------|-----------------|-----------------|
| Test location                  | Depth (m)       | The strain "ahead" and "lag" distances | the strain intensive induction zone |
|                                | Forward distance (m) | Post-mining distance (m) | Forward distance (m) | Post-mining distance (m) |
| Baodian Coal Mine              | 10              | 60              | –                | 38               | –                |
| Coal Mine                      | 12              | 60              | 33               | 23               | 60               | 26               |
|                               | 14              | 60              | 45               | 23               | 26               | 22               |
|                               | 15              | 60              | 42               | 26               | 17               | 17               |
|                               | 16              | 60              | 28               | 24               | 18               | 18               |
|                               | 17              | 60              | 33               | 18               | 25               | 25               |
|                               | 19              | 60              | 13               | 20               | 8                | 8                |
| Dongtan Coal Mine              | 16              | 115             | –                | 49               | –                |
| Coal Mine                      | 17              | 118             | 50               | 48               | 50               | –                |
|                               | 20              | 110             | 49               | 39               | 25               | –                |
|                               | 21              | 112             | 40               | 37               | 28               | –                |
|                               | 24              | 102             | 48               | 34               | 37               | –                |
|                               | 25              | 103             | 55               | 33               | 37               | –                |
|                               | 29              | 96              | 52               | 28               | 38               | –                |
| Zhaolou Coal Mine              | 10.7            | 98              | –                | 31               | –                |
| Coal Mine                      | 12.8            | –               | –                | 26               | –                |
|                               | 15.4            | 105             | –                | 40               | –                |
|                               | 18              | 96              | –                | 32               | –                |
|                               | 22.6            | 95              | –                | 28               | –                |
|                               | 25.4            | 95              | –                | 46               | –                |
| Yangcun Coal Mine              | 3.5             | 98              | –                | 31               | –                |
| Coal Mine                      | 4.8             | 85              | –                | 22               | –                |
|                               | 6.8             | 90              | 25               | 25               | –                |
|                               | 8.4             | 80              | 30               | 38               | –                |
|                               | 10.1            | 80              | 36               | 26               | 11               |
|                               | 11.3            | 76              | 35               | 22               | 26               |
|                               | 15.1            | 60              | 46               | 22               | 17               |
|                               | 16.0            | 70              | 40               | 15               | 17               |
| Xinglongzhuang Coal Mine       | 6.9             | 115             | 48               | 34               | 22               |
| Coal Mine                      | 8.8             | 98              | 35               | 29               | 18               |
|                               | 10.6            | 113             | 42               | 35               | 21               |
|                               | 12.5            | 96              | 46               | 30               | 25               |
|                               | 16.2            | 105             | 27               | 26               | 19               |
|                               | 16.3            | 86              | 28               | 22               | 14               |
|                               | 19.1            | 105             | 22               | 28               | 18               |
|                               | 20.0            | 90              | 25               | 20               | 16               |

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The results also show that with the advancement of the working faces, the induced strains appear to be increasingly larger during the advancement of mining and after the completion of mining. When the working face is located further away from the point of measurement, there is an obvious induced stress found at each measurement point, which becomes negative only after the working face is advanced to a certain distance from the point of measurement. With different working face locations, the ability to detect the distance in the measured boreholes at different depths also differs, and the magnitude of the induced strain at the measured points change dynamically with advancement of the working face.

The amount of strain is positively related to the strength of the mine floor, so an increase in the in the strength of the mine floor causes an increase of the measured strain. The area in which there are high strains in the advancement of the working face can be therefore defined as having the highest stresses. This area is the same as the area of increased stress found in Zhu et al. (2017). It is also the location with the highest loading which is the primary cause of the plastic deformation of the mine floor. However, the redistribution of stresses in the mine floor caused by mining changes the area from no damage to one of an increase in stresses. Since the stresses are less than the stress in the area with high stress concentrations, deformation in this area is mainly elastic.

Therefore, based on field measurements of the mine floor, the area with mining induced stress is illustrated in Figure 8, which can be used to monitor the level and magnitude of the induced strain in the mine floor. The results of mining induced stresses can be examined as three different zones: the zone with the initial stress (initial stress zone) unaffected by mining, elastic zone and zone that is severely affected by stress (severely affected zone). Among them, the latter is affected by high and unloaded stresses, which causes a large amount of disturbance in the mine floor during mining.
The strain gauges used in this study provide two types of strain measurements: axial and radial strain measurements. Zhu et al. (2017) proposed that after the advancement of the working face, the stress in front of the working face will increase due to stress concentrations, which will damage the mine floor. After more advancement of the working face, the layer of rock in the mine floor falls into the goaf due to unloading, which could lead to the deformation of the floor and even damage to the floor. In-situ strain measurements can be used to determine the stress on the floor in both the axial and radial directions, and then the stress state and deformation and failure characteristics of the floor during mining can be determined and summarized.

Taking Borehole 1 as an example, the drilled angle intersected with the rock of the mine floor at a small depression, so the stress characteristics of the induced strains in measurements of the borehole are mainly radial compression or radial tension stress. An analysis of the morphology of the rock due to induced strains is shown in Figure 9(a), which corresponds to the measured stress at depths of 10 m and 14 m (because the stress at depths of 16 m and 19 m is not significantly different) in Figure 5. It can be found that the amplitude of the measured strain by the radial strain gauge at the same point of measurement is obviously higher than that of the axial strain gauge. Therefore, the gauges will be in the state of shear stress whether under pressure concentration in front of the working face or from a certain range of pressure due to unloading behind the working face. Radial pressure can easily cause damage to the gauges. Therefore, some of the strain gauges that are placed at shallower depths are damaged. The stress analysis in

\[ \sigma_a : \text{axial stress; } \sigma_r : \text{radial strain; } \sigma_z : \text{original rock stress.} \]
Figure 9(a) and the borehole imaging results in Figure 7 show that the failure of the floor can be considered as compression-shear under pressure concentration, and tension-shear under unloaded pressure during mining. Similar regimes have been found in the small pitch boreholes in the Dongtan, Zhaolou and Yangcun mines, and some of the strain gauges placed at shallower depths have also been damaged.

Borehole 2 is also discussed as an example. The drilled angle intersects with the rock in the mine floor at high elevations, so the stress characteristics of the strain induced during borehole measurements are mainly axial compression or axial tension stress. An analysis of the morphology of the rock due to induced strains is shown in Figure 9(b). Based on the measurements of the sensor at a depth of 12 m (because the stress at depths of 15 m and 17 m is not significantly different) in Figure 4, it can be found that the amplitude of the induced axial strain at the same point of measurement is obviously higher than that of the induced radial strain. By combining this finding with the deformation of the rock mass observed by borehole imaging, the failure of the mine floor can be categorized as compression under pressure concentration in front of the working face and the tension caused by expansion due to the effects of unloaded pressure. This regime is also observed in the boreholes at high elevations in the Xinglongzhuang Mine in Shandong, China.

Therefore, mining induced characteristics of the mine floor might be caused by both the pressure concentration during the advancement of mining and the unloaded pressure after the completion of mining, and validated by the water inrush from the working faces to a certain extent.

### 3.2. Failure characteristics of rocks in mine floor

During the process of coal seam mining, the initial stress of the rock mass of the mine floor will change, which results in stress redistribution. The changes in stress will cause displacement, deformation and even damage of the rock mass in the floor, forming fractured zones, and the floor gradually loses its ability to prevent water infiltration, thus resulting in water inrush events. Therefore, it is important that engineering practices incorporate information on the depth of mining that would cause failure of the floor and accurately predict the depth of mining through in-situ strain measurements.

In this paper, the depth in which the mine floor is damaged by mining induced stresses is determined to be the depth in which there is failure of the mine floor. Combined with the measured amplitude of induced strains in situ and the results of the borehole imaging, the depth at which failure of the mine floor results due to mining in each of the five coal mines is quantitatively analyzed.

Based on actual measurements taken at the Baodian Coal Mine, it is obvious that the induced strains measured by the axial and radial gauges at depths of 10 m and 12 m is high, there is a wide range of variation in the measured values, and the measured differences are obvious. The strain sensing signals were suddenly lost during mining at a depth of 10 m when the working face advanced 8 m to the measurement points because the sensor was damaged by mining induced stresses. The amplitude of the induced strains at a depth of 12 m is approximately the same as that at 10 m, and
the difference is not obvious. A comparison was made with the borehole imaging results, and the depth of the failure zone of the mine was determined to be between 10 and 12 m.

Table 4. Summary of in-situ measurements of depth of failure of mine floor.

| Tested Face                          | Depth of failure | Comments                                                                                                                                                                                                 |
|--------------------------------------|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| No. 10302 Working Face of Xinglongzhuang Coal Mine | 12.5-16.2 m      | Four measured points at depths over 16.2 m show intense induced plastic strain in the section that is very much affected by mining induced stresses. Three strain probes show signs of damage when placed at shallower depths; on the contrary, four probes at depths of 16.2 m or less mainly show induced elastic strain, with no plastic strain. |
| No. 1305 Working Face of Dongtan Coal Mine            | 17-20 m         | The induced strain signal is highly discrete and the fluctuations in induced strains are high at the surveyed point of a depth of 17 m where the mining induced stresses have severe effects, and the fluctuation is as high as 5000 με, which indicates that there is large plastic deformation of the floor. The induced strains change obviously along with mining induced stresses at each measured point at depths less than 20 m, and the variation in the amplitude of the induced strain is minimal. The maximum amount of fluctuation is about 1000 με, which shows that the deformation at the corresponding depth of the floor is mainly elastic. |
| No. 5304-2 Working Face of Baodian Coal Mine          | 10-12 m         | The measured points for a sag depth of 10 m at the bottom from the borehole start to show intense induced strains from about 38 m from the measured point of the front of the working face, and the output signals of all channels close to the measured point of the front of the working face (about 8 m from the working face) are lost. This is analyzed and it is determined that the damage of the probe is caused by the damage of the bottom plate. At a depth of 12 m, all the probes are operating normally, and the elastic characteristics of strain induction are obvious. The location of the probes is mainly affected by elastic damage. |
| No. 1304(2) Working Face of Zhaolou Coal Mine         | 18-22.6 m       | At a depth of 18.0 m, four measured points on surface of working face are strongly sensitive to mining induced stresses, and demonstrate intense plastic induced strains, and the strain probes at three measured points at shallower depths are damaged. On the contrary, at depths of 22.6 m and 25.4 m, there is mainly elastic induced strains, and the strain range is small. At a depth of 20.3 m, there is damage when the probe was installed, and no comparative data of strain induction are obtained. |
| No. 4602 Working Face of Yangcun Coal Mine            | 8.4-10 m        | The probes in four measured points at shallower depths are damaged to varying degrees with advancement of the working face. The channels to measure vertical points at 6.8 m and 8.4 m were not operating, while the those at 3.5 m and 4.8 were not operating at about 10 m from the front of the working face, which indicates that the strata at the location of the measured point are in the state of plastic yield or failure. At depths of 10.1 m and 11.3 m, the probes work normally, and the elastic induced strains are obvious, which indicates that the corresponding position has not been damaged. |
Along with the strain measurements and borehole imaging results of the four other mines, the depth of the failure zone of the Yangcun, Zhaolou, Xinglongzhuang and Dongtan mines during mining is shown in Table 4. Although the induced strain measurements of the mine floor obtained at depths lower than the failure zone are fluctuating, the structure of the mine floor is basically not affected by the borehole imaging, so we think that the rock mass has only undergone elastic-plastic deformation and continues to have a high bearing strength and impermeability. Therefore, it is not considered for inclusion in the failure zone.

4. Conclusions

A comprehensive analysis of the in-situ strain measurement results of the Yanzhou Coal Mine has been carried out, and the following conclusions are made accordingly.

1. The results of the field strain measurements quantitatively show that the results of mining induced stresses can be examined as three different zones: the zone with the initial stress (initial stress zone) unaffected by mining, elastic zone and zone that is severely affected by stress (severely affected zone). On the other hand, the results of the borehole imaging more intuitively show the deformation state of the mine floor. When these two methods are both applied, the deformation and failure regime of the mine floor are further demonstrated with ongoing mining activity.

2. The depth of the failure zone of each mine has been determined through in-situ tests. The depth of the failure zone of the Baodian Mine is between 10-12 m, Dongtan Mine between 17-20 m, Zhaolou Mine between 18-22.6 m, Yangcun Mine between 8.4-10 m, and Xinglongzhuang Mine between 12.5-16.2 m.

3. A correlation analysis of the field strain measurements and borehole imaging results show that with increases in depth, the influence of mining on the amount and degree of deformation is negatively correlated, and the mine floor undergoes a process from being elastic to plastic and finally fails in both the vertical and horizontal directions.

Disclosure statement

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References

Chen YF, Hu SH, Hu R, Zhou CB. 2015. Estimating hydraulic conductivity of fractured rocks from high-pressure packer tests with an Izbash’s law-based empirical model. Water Resour Res. 51(4):2096–2118.

Cheng GW, Chen CX, Li LC, Zhu WC, Yang TH, Dai F, Ren B. 2018. Numerical modelling of strata movement at footwall induced by underground mining. Int J Rock Mech Min. 108: 142–156.

Cheng GW, Ma TH, Tang CA, Liu HY, Wang SJ. 2017. A zoning model for coal mining-induced strata movement based on microseismic monitoring. Int J Rock Mech Min. 94: 123–138.

Feng Q, Jiang B, Wang G, Hu C. 2016. Analytical solution for a circular roadway considering the transient effect of excavation unloading. Int J Min Sci Tech. 26(4):543–549.

Herda H. 2011. Algorithmic simulation of flow in rock fractures. Rock Mech Rock Eng. 44(2): 211–220.

Huang Q, Cheng J. 2017. Analytical model of stress field and failure depth in multilayered rock masses of mining floor based on the transfer matrix method. Geotech Geol Eng. 35(6): 2781–2788.

Huang Z, Jiang ZQ, Qian ZW, Cao DT. 2014. Analytical and experimental study of water seepage propagation behavior in the fault. Acta Geodyn Geomater. 11(4):361–371.

Huang Z, Li XZ, Li SJ, Zhao K, Zhang R. 2018. Investigation of the hydraulic properties of deep fractured rocks around underground excavations using high-pressure injection tests. Eng Geol. 245:180–191.

Huang Z, Li SJ, Zhao K, Wu Y, Zeng W, Xu HW. 2019. Estimation of hydraulic conductivity of deep fractured rocks from high-pressure injection tests. Mine Water Environ. 1–9. doi:10.1007/s10230-019-00646-w

Huang Z, Zeng W, Wu Y, Li SJ, Zhao K. 2019a. Experimental investigation of fracture propagation and inrush characteristics in tunnel construction. Nat Hazards. 97(1):193–210.

Huang Z, Zeng W, Zhao K. 2019b. Experimental investigation of the variations in hydraulic properties of a fault zone in Western Shandong, China. J Hydrol. 574:822–835.

Jian S, Wang LG, Wang ZS, Hou HQ, Shen YF. 2011. Determining areas in an inclined coal seam floor prone to water-inrush by micro-seismic monitoring. J China Min Sci Tech. 21(2):165–168.

Kang H, Zhang X, Si L, Wu Y, Gao F. 2010. In-situ stress measurements and stress distribution characteristics in underground coal mines in China. Eng Geol. 116(3–4):333–345.

Konicek P, Soucek K, Stas L, Singh R. 2013. Long-hole destress blasting for rockburst control during deep underground coal mining. Int J Rock Mech Min Sci. 61:141–153.

Li HL, Bai HB, Yang J, Cheng Y. 2013. Water injection test and numerical analysis of the mining-induced failure depth of floor. Electron J Geotech Eng. 18(1):849–857.

Li YW, Jia D, Wang M, Liu J, Fu CK, Yang XL, Ai C. 2016. Hydraulic fracturing model featuring initiation beyond the wellbore wall for directional well in coal bed. J Geophys Eng. 13(4):536–548.

Li ZH, Li LF, Zhai CZ, Kumuri T. 2014. Experimental study on the law of deformation and fracture of the coal floor in mining above aquifer. J Eng Sci Tech Review. 7(4):114–119.

Li A, Liu Y, Mou L. 2015. Impact of the panel width and overburden depth on floor damage depth in no. 5 coal seam of Taiyuan group in Chenghe Mining Area. Electron J Geotech Eng. 20(6):1603–1617.
Li Y, Tang DZ, Xu H, Yu TX. 2014. In-situ stress distribution and its implication on coalbed methane development in Liulin area, eastern Ordos basin, China. J Petrol Sci Eng. 122: 488–496.

Liu WT, Du YH, Liu YB, Pang LF. 2019. Failure characteristics of floor mining-induced damage under deep different dip angles of coal seam. Geotech Geol Eng. 37(2):985–994.

Liu SG, Huang JK, Huang QM, Li TT, Tang SL, Liu X. 2019. Floor pressure-relief during top slice mining of extra-thick coal seams and its implications for gas drainage application. Geotech Geol Eng. 37(4):3113–3125.

Liu SL, Liu WT, Shen J. 2017. Stress evolution law and failure characteristics of mining floor rock mass above confined water. Sci J Civ Eng. 21(7):2665–2672.

Liu WT, Song WC, Mu DR, Zhao JY. 2017. Section observation system on floor mining damage zone and its application. J Cent S Univ Sci Tech. 48(10):2808–2816.

Liu XS, Tan YL, Ning JG, Tian CL, Wang J. 2015. The height of water-conducting fractured zones in longwall mining of shallow coal seams. Geotech Geol Eng. 33(3):693–700.

Lu YL, Wang LG. 2015. Numerical simulation of mining-induced fracture evolution and water flow in coal seam floor above a confined aquifer. Comput Geotech. 67:157–171.

Ma D, Cai X, Li Q, Duan HY. 2018. In-situ and numerical investigation of groundwater inrush hazard from grouted karst collapse pillar in longwall mining. Water. 10(9):1187.

Ma D, Duan HY, Liu JF, Li XB, Zhou ZL. 2019. The role of gangue on the mitigation of mining-induced hazards and environmental pollution: An experimental investigation. Sci Total Environ. 664:436–448.

Ma D, Rezania M, Yu HS, Bai HB. 2017. Variations of hydraulic properties of granular sandstones during water inrush: effect of small particle migration. Eng Geol. 217:61–70.

Meng ZP, Li GQ, Xie XT. 2012. A geological assessment method of floor water inrush risk and its application. Eng Geol. 143:51–60.

Meng XX, Liu WT, Zhao JY, Ding XY. 2019. In situ investigation and numerical simulation of the failure depth of an inclined coal seam floor: a case study. Mine Water Environ. 38(3):686–694.

Slaker BA, Mohamed KM. 2017. A practical application of photogrammetry to performing rib characterization measurements in an underground coal mine using a DSLR camera. Int J Min Sci Tech. 27(1):83–90.

Song WC, Zhao CB, Li G, Wang DH. 2016. Research on simulation and field measurement technology of floor mining failure depth. In: The 8th Russian-Chinese Symposium. Coal in the 21st century: Mining, Processing and Safety. Kuzbuss, Russia, October 11–13; p. 220–228.

Su PL, Wei ZF. 2018. Depth of floor failure of stope with medium-thickness coal seam. Geotech Geol Eng. 36(2):1341–1347.

Sun WB, Zhang SC, Guo WJ, Liu WT. 2017. Physical simulation of high-pressure water inrush through the floor of a deep mine. Mine Water Environ. 36(4):542–549.

Wang YC, Geng F, Yang SQ, Jing HW, Meng B. 2019. Numerical simulation of particle migration from crushed sandstones during groundwater inrush. J Hazard Mater. 362:327–335.

Wang LG, Zhang ZK, Lu YL, Yang HB, Yang SQ, Sun J, Zhang JY. 2009. Combined ANN prediction model for failure depth of coal seam floors. China J Mini Sci Tech. 19(5):684–688.

Wang Q, Pan R, Jiang B, Li S,C, He M,C, Sun H,B, Wang L, Qin Q, Yu H,C, Luan Y,C. 2017. Study on failure mechanism of roadway with soft rock in deep coal mine and confined concrete support system. Eng Fail Anal. 81:155–177.

Xu ZM, Sun YJ, Gong SY, Zhu ZK. 2012. Monitoring and numerical simulation of formation of water inrush pathway caused by coal mining above confined water with high pressure. Chin J Rock Mech Eng. 31(8):1698–1704.

Yin HY, Lefticariu L, Wei JC, Zhu L, Guo JB, Li ZJ, Guan YZ. 2016. A multi-method approach for estimating the failure depth of coal seam floor in a longwall coal mine in China. Geotech Geol Eng. 34(5):1267–1281.

Yu XG, Han J, Shi LQ, Wei JC, Zhu L, Li SC. 2009. Forecast of destroyed floor depth based on BP neural networks. J China Coal Society. 34(6):731–736.
Zhang C, Tu SH, Zhang L, Bai QS, Yuan Y, Wang FT. 2016. A methodology for determining the evolution law of gob permeability and its distributions in longwall coal mines. J Geophys Eng. 13(2):181–193.

Zhang PS, Wu JW, Liu CD. 2006. Coal mining activities floor destruction rule of dynamic observation. J Rock Mech Engn. 25(1):3009–3013.

Zhao JL, Tang DZ, Xu H, Li Y, Li S, Tao S, Lin WJ, Liu ZX. 2016. Characteristic of in situ stress and its control on the coalbed methane reservoir permeability in the eastern margin of the Ordos Basin, China. Rock Mech Rock Eng. 49(8):3307–3322.

Zheng C, Yang TH, Yu QL, Zhang PH, Liu HL. Zhang SJ 2012. Stability evaluation of excavated rockmass in mines based on microseismic monitoring. J China Coal Society. 37(1): 280–286.

Zhu SY, Jiang ZQ, Cao DT, Sun Q, Yang CW. 2013. Restriction function of lithology and its composite structure to deformation and failure of mining coal seam floor. Nat Hazards. 68(2):483–495.

Zhu SY, Jiang ZQ, Zhou KJ, Peng GQ, Yang CW. 2014. The characteristics of deformation and failure of coal seam floor due to mining in Xinmi coal field in China. Bull Eng Geol Environ. 73(4):1151–1163.

Zhu SY, Liu RX, Zhang SJ, Hu D. 2016. Characteristics of deformation and failure of deep coal seam floor affected by fully mechanized mining. Geotech Test J. 39(1):1–12.

Zhu SY, Lu LL, Wu Y, Zhang TT. 2017. Comprehensive study on the deformation and failure characteristics of a mining-impacted deep double-longwall working face floor. J Geophys Eng. 14(3):641–653.

Zhu WC, Wei CH. 2011. Numerical simulation on mining-induced water inrushes related to geologic structures using a damage-based hydromechanical model. Environ Earth Sci. 62(1): 43–54.

Zhu WSY, Zhang TT. 2018. Permeability of the coal seam floor rock mass in a deep mine based on in-situ water injection tests. Mine Water Environ. 37(4):724–733.