Studies on Gas Seepage Characteristics in Different Stress Zones of Bottom Coal in Steeply Inclined and Extra-Thick Coal Seams under Mining Action

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ABSTRACT: The gas released from the bottom coal of the horizontal slicing mining face in steeply inclined and extra-thick coal seams seriously threatens the safety of the upper slicing mining face. To explore the seepage characteristics of bottom coal gas, the coal deformation and gas permeability evolution law of four coal samples in different stress zones of bottom coal in the working face were analyzed through true triaxial fluid–solid coupling seepage experiments. At the same time, the seepage capacity of bottom coal gas was partitioned according to the field test. The results show the following: (1) The gas permeability of the bottom coal stress concentration zone first decreased and then increased with axial pressure loading and confining pressure unloading. The gas permeability of the bottom coal stress relief zone increased rapidly with decreasing axial pressure and confining pressure. The gas permeability of the bottom coal stress recovery zone gradually decreased with the cyclic loading and unloading of axial pressure and tended to be stabilized. (2) The evolution law of gas permeability in the bottom coal was closely related to the damage and deformation of coal. (3) From the original stress zone to the stress recovery zone, the gas seepage capacity of bottom coal can be divided into four zones, namely, the original seepage zone, the seepage reduction zone, the seepage sharp increase zone, and the seepage reduction zone. The gas seepage capacity in the stress concentration zone was more substantial than that of the stress recovery zone. The results of this study are of great significance for strengthening the dynamic disaster prevention and control of bottom coal gas in the horizontal slicing mining face of steeply inclined and extra-thick coal seams.

1. INTRODUCTION

The law of gas migration in a horizontal slicing mining face of steeply inclined and extra-thick coal seams is different from that of nearly horizontal and gently inclined coal seams. It has the threat of gas release from bottom coal flows to the upper slicing mining face. Scientific studies and production practices indicate that the gas emitted from the bottom coal of a horizontal slicing mining face in steeply inclined and extra-thick coal seams accounts for more than 37% of total gas emission from the face, as shown in Figure 1. It seriously threatens the safe production of the upper slicing mining face. The gas released from bottom coal is an important part of the gas emission from the working face, while the law of gas migration is mainly affected by the stress environment. During the mining of steeply inclined and extra-thick coal seams, the advancement of the working face disrupts the original stress equilibrium state of coal and rock mass, resulting in evident stress concentration and pressure relief in the bottom coal. The stress environment of different regions leads to significant differences in the seepage characteristics of bottom coal gas. Therefore, it is necessary to study the seepage characteristics of bottom coal gas.

At present, the seepage characteristics of coal and rock masses have been extensively studied through true triaxial seepage experiments, which yielded numerous instructive research results. Zhang et al. simulated the stress state of coal face mining by unloading the confining pressure imposed on the coal sample; the gas permeability characteristics of raw coal after peak loading and unloading were obtained. The results show that the gas seepage process can be divided into three stages, namely, attenuation, stabilization, and acceleration. Yin et al. studied the evolution law of coal gas permeability under the stress path in front of the mining working face and analyzed the stress–strain–permeability relationship.
discussed the stress decreasing rate of raw coal permeability exhibited a trend of gradually gas-bearing coal. The results showed that the absolute recovery studied the seepage characteristics of cyclic mining stress on coal under true triaxial stress conditions.6 Ju et al. and Zhang et al. discussed the permeability characteristics of layered composite three typical coal seam mining stress paths.7,8 Jiang et al. studied the permeability characteristics of coal gas under coal.12 Meng et al. studied the gas seepage law of raw coal and accelerated the destruction process of gas-containing coal. The results showed that gas seepage reduced the strength of gas-containing coal during the loading process, the permeability of coal after unloading was more significantly than the original permeability of coal.24

The abovementioned topics have been extensively studied and have yielded fruitful research results. However, there are few studies on the gas seepage characteristics of bottom coal in the horizontal slicing mining face of steeply inclined and extra-thick coal seams under true triaxial stress conditions. Therefore, the bottom coal of the horizontal slicing mining face on the east side of the no. 45 coal seam at +575 m level in the northern area of Xinjiang Wudong Coal Mine was used as the research object in this study. The true triaxial fluid—solid coupling coal seepage experiment system was used to carry out seepage experiments that are consistent with the actual mechanical environment of bottom coal. Furthermore, the gas seepage characteristics of bottom coal in different stress zones were analyzed, which lays a foundation for revealing the law of gas migration in the bottom coal of the horizontal slicing mining face in steeply inclined and extra-thick coal seams. At the same time, it has important theoretical and practical relationship of coal.2 Chen et al. conducted the loading and unloading seepage experiment based on the stress environment around mining of the protective coal seam and obtained the permeability distribution law.3 To reveal permeability characteristics of the protective coal seam, Li et al. studied the gas seepage experiment of raw coal under three stress paths: step cycle, step increase cycle, and cross cycle. The results showed that the permeability of coal exhibited an "N"-shaped increase trend under step cycle loading but a linear increase trend under the other two stress paths.4 Xie et al. used triaxial experiments to simulate the stress state of mining and protection coal seams and quantitatively analyzed the increasing permeability characteristics of coal.5 Lu et al. studied the dynamic permeability evolution characteristics of layered composite coal under true triaxial stress conditions.6 Ju et al. and Zhang et al. discussed the permeability characteristics of coal gas under three typical coal seam mining stress paths.7,8 Jiang et al. studied the seepage characteristics of cyclic mining stress on gas-bearing coal. The results showed that the absolute recovery rate of raw coal permeability exhibited a trend of gradually decreasing first and then increasing.9 Zhang and Zhang discussed the stress—permeability relationship of broken coal, rock, and coal—rock composite specimens with different particle sizes under cyclic loading and unloading conditions.10 Zou et al. studied the influence of effective stress and gas slippage effects on coal permeability under cyclic loading and unloading conditions.11

Peng et al. investigated the influence mechanism of gas seepage on coal and gas outburst disasters. The results showed that gas seepage reduced the strength of gas-containing coal and accelerated the destruction process of gas-containing coal.12 Meng et al. studied the gas seepage law of raw coal prone to outburst under different gas pressure conditions.13 Based on the triaxial seepage experiment system, Wang et al. carried out a study on the anisotropic seepage law of gas-bearing coal.14 Fangbin et al. analyzed the seepage law of raw coal under different lateral stress and axial stress conditions.15 Wang et al. studied the evolution characteristics of the permeability for raw coal during the progressive deformation process.16 Zeng et al. studied the permeability characteristics of coal under triaxial compression. The results showed that the maximum principal stress and cleat direction significantly controlled the permeability of raw coal.17 Wang et al. studied the deformation and gas flow characteristics of anthracite under true triaxial stress conditions.18,19 Liu et al. studied the evolution of anisotropic permeability for anthracite under true triaxial stress conditions. The results showed that the permeability of coal was strongly dependent on the change in stress and the direction of the flow plane.20 Meng and Li analyzed the deformation law of anthracite induced by different gas adsorptions and its influence on permeability.21 Meng and Li studied the permeability behavior of high-rank coals. The results showed that the irreversible permeability loss rate of low-rank coals under the same unloading conditions was significantly lower than that of high-rank coals.22 Chen et al. studied the damage of remodeled coal samples during unloading and its influence on permeability.23 Xiangchun et al. investigated the relationship between coal damage and gas seepage under true triaxial stress. It was found that with increasing damage to coal during the loading process, the decrease in the permeability of coal after unloading was more significant than the original permeability of coal.24

Figure 1. Proportion of gas emission from the bottom coal of the horizontal slicing mining face in steeply inclined and extra-thick coal seams.
significance to guide the gas prevention and control of bottom coal in the mining process of the working face.

2. RESULTS

2.1. Experimental Results and Analysis of Coal Gas Seepage Characteristics under Stress Path I

The coal sample 1# in the original stress zone of the bottom coal located in the horizontal slicing mining face of steeply inclined and extra-thick coal seams was subjected to conventional triaxial loading experiments. The purpose of this study is not only to determine the axial stress $\sigma_u$ during unloading but also to use it as a comparative analysis sample. Under the conditions of stress path I, the relationship between principal stress difference, permeability, and strain and the relationship between axial stress, permeability, and axial strain of coal sample 1# are shown in Figure 2.

It can be seen from Figure 2 that the overall permeability of coal sample 1# was reduced from $8 \times 10^{-16}$ to $5.26 \times 10^{-16} \text{ m}^2$, with a reduction difference of $2.74 \times 10^{-16} \text{ m}^2$. The permeability and the axial strain show a trend of first decreasing and then increasing. With the loading of axial stress, the permeability of the coal sample showed a phased characteristic with the axial strain. The principal stress difference, the axial stress−strain curve, and the permeability−strain curve showed an obvious corresponding relationship, basically an oppositely changing trend. It can be seen that the permeability change was closely related to the damage and deformation of coal. The overall stress, permeability, and strain curve of coal sample 1# can be divided into four stages, namely, initial compaction stage (stage I: 4−6 MPa), elastic deformation stage (stage II: 6−14 MPa), elastic−plastic deformation stage (stage III: 14−18 MPa), and plastic deformation stage (stage IV: after 18 MPa).

In the first and second stages, the axial stress $\sigma_1$ increased from 4 to 6 MPa and 6 to 14 MPa, respectively. The permeability gradually decreased with the increase in $\sigma_1$ and $\epsilon_1$, but decreasing rate gradually slowed down in the second stage. During these two stages, no new pores and cracks were generated inside the coal sample. Meanwhile, the original pores and cracks were gradually compacted and closed, which reduces the volume. The channel of gas flow through the coal became narrow, making it difficult for the gas to pass. Therefore, the permeability characteristics of the coal sample gradually weakened. In the third stage, the axial stress $\sigma_1$ increased from 14 to 18 MPa. When $\sigma_1$ increased to the yield strength of the specimen, the coal permeability reached the lowest value of $4.59 \times 10^{-16} \text{ m}^2$, and the specimen volume was the smallest at this time. There was an obvious inflection point between permeability and volume strain. After the yield point, the volumetric strain turned to a smaller direction. The specimen entered the expansion stage, in which the permeability increased slowly with an increase in $\sigma_1$ and $\epsilon_1$. At this stage, new pores and cracks were generated in the specimen with increasing volume. In the meantime, the
channel for gas flow through the coal increased, and the permeability gradually increased. In stage IV, when the axial stress $\sigma_1$ increased to the peak strength of the specimen, the coal was destroyed, and the cracks penetrated each other to generate macroscopic cracks. As a result, the permeability characteristics of the specimen were significantly enhanced.

2.2. Experimental Results and Analysis of Coal Gas Seepage Characteristics under Stress Path II. Under the conditions of stress path II for coal sample 2#, the relationship between principal stress difference, permeability, and strain and the relationship between axial stress, permeability, and axial strain are shown in Figure 3.

It can be seen from Figure 3 that the permeability change trend of coal sample 2# under stress path II conditions was roughly similar to that of stress path I. As the principal stress difference increased, the permeability first decreased and then gradually increased. The overall value decreased from $6.44 \times 10^{-16}$ to $4.98 \times 10^{-16}$ m² with a decreasing difference of $1.46 \times 10^{-16}$ m². The overall stress, permeability, and strain changes were also divided into four stages, namely, initial compaction stage (stage I: 6–8 MPa), elastic deformation stage (stage II: 8–13 MPa), elastic–plastic deformation stage (stage III: 13–15.3 MPa), and plastic deformation stage (stage IV: after 15.3 MPa). In phases I and II, the permeability of specimen 2# gradually decreased with the loading of axial stress $\sigma_1$ and the unloading of confining pressures $\sigma_2$ and $\sigma_3$. Compared with the monotonic loading of stress path I, the permeability decrease rate was lower, and the reduction was only 77.4% of specimen 1#. The main reason is that the original pores and cracks in the coal sample are gradually destroyed by the axial load during the compaction process. In the meantime, the unloading effect of the confining pressure also exists to expand the pores and fracture structure of the coal sample. With the continuous increase in principal stress difference, the permeability of coal sample 2# gradually increased during the third and fourth stages. The continuous unloading of confining pressure caused the permeability increase of the sample to be significantly stronger than that of sample 1#. The increase in permeability was 2.35 times that of sample 1#. Due to the increase in axial stress and unloading of confining pressure, specimen 2# showed a strong expansion in the radial direction after yielding. It can be seen that when specimen 1# reached the peak strength of 18 MPa, its radial strain $\varepsilon_c$ was 0.045. When specimen 2# reached the peak strength of 15.3 MPa, its radial strain $\varepsilon_c$ was 0.054, and the radial strain $\varepsilon_c$ was 1.2 times that of specimen 1#. Therefore, the gas circulation channel expanded after yielding, resulting in a rapid increase in permeability.

2.3. Experimental Results and Analysis of Coal Gas Seepage Characteristics under Stress Path III. Under the conditions of stress path III for coal sample 3#, the relationship between principal stress difference, permeability, and strain and strain and
the relationship between axial stress, permeability, and axial strain are shown in Figure 4.

It can be seen from Figure 4 that when the triaxial stress was unloaded to 4 MPa, the permeability of coal sample 3# increased with the decrease in axial pressure and confining pressure. The overall value increased from $4.22 \times 10^{-16}$ to $5.71 \times 10^{-16}$ m$^2$. After the specimen was unloaded from the elastic–plastic deformation stage, the pores and cracks inside the coal were gradually recovered from the compacted and closed state. However, the recovery of overall permeability was very small, only increasing by $1.43 \times 10^{-16}$ m$^2$. During the whole unloading process of coal sample 3#, the changing trend of permeability with strain showed two stage characteristics. In the initial stage of unloading, the permeability increased slowly with the unloading of triaxial stress. The rising rate was small, which fluctuated slightly and steadily around $4.22 \times 10^{-16}$ m$^2$. This is primarily because the coal is still in a compact state, and the internal pores and most of the cracks are still closed, in which the channels for the gas to flow through the coal are limited. With the continuous unloading of axial pressure and confining pressure, the compaction state of the specimen gradually weakened. As a result, the pores and cracks gradually opened, and the gas seepage channels increased and gradually circulated. At this time, the permeability of the coal sample gradually increased, and the rate of increase was significantly higher than that at the initial stage of unloading. However, it did not fully recover to the initial value of the loading stage, indicating that irreversible damage occurred in the coal and the compacted pores and cracks only partially reopened.

2.4. Experimental Results and Analysis of Coal Gas Seepage Characteristics under Stress Path IV. Under the conditions of stress path IV for coal sample 4#, the relationship between principal stress difference, permeability, and stress and the relationship between axial stress, permeability, and axial strain are shown in Figure 5.

It can be seen from Figure 5 that during the cycle of loading and unloading, the permeability change of coal sample 4# exhibited an obvious corresponding relationship with the stress–strain curve. With the cyclic loading and unloading of axial stress, the permeability of the specimen showed an overall downward trend. The overall value decreased from $8 \times 10^{-16}$ to $4.45 \times 10^{-16}$ m$^2$ with a decrease difference of $3.55 \times 10^{-16}$ m$^2$. After three cycles, the drop in permeability gradually slowed down, and eventually, it tended to be stabilized with almost no change. The reason for this phenomenon is that the axial stress $\sigma_1$ was loaded up to 14 MPa. At this time, the specimen was still in the elastic–plastic deformation stage without damage. After three cycles of loading and unloading experiments with axial stress, the coal sample was in the process of continuous compaction and closure, volume compression. $\epsilon_1$ was always greater than zero, indicating that the process is predominated with pore and crack compaction. Since the gradual closure of pores and cracks in the coal led to a decrease in gas seepage channels, the permeability gradually decreased and tended to be stabilized. At the same time, it can be found that the stress and strain curves and permeability and strain curves of coal sample 4# all exhibited hysteresis loops. It indicated that after the sample underwent three cycles of loading and unloading experiments, both elastic deformation and plastic deformation occurred. The area of hysteresis loops gradually decreased with an increase in the number of cycles. At this time, the plasticity of the specimen decreased, while the elasticity increased. The influence of the cyclic loading and unloading of stress on the permeability of coal was gradually reduced.

The relationship between the axial stress, permeability, and axial strain of coal sample 4# at different cycle stages is shown in Figure 6.

It can be seen from Figure 6 that during the three cycles of loading and unloading for coal sample 4#, the permeability of the sample decreased with an increase in $\sigma_1$, during the loading stage and gradually increased with the decrease in $\sigma_1$ during the unloading stage, but it cannot recover to the initial value. The permeability in the unloading stage of each cycle was less than that in the loading stage. This is because after three cycles, the specimen is always in the compaction process, which reduces the porosity and induces irreversible plastic deformation. In the first cycle, the distance between the loading curve and unloading curve of the coal sample was relatively large without formation of a closed loop. In this cycle, the permeability loss of the coal sample was the largest. When the axial stress was unloaded to the initial value of 4 MPa, the permeability decreased from $8 \times 10^{-16}$ to $5.07 \times 10^{-16}$ m$^2$ with a difference of $2.92 \times 10^{-16}$ m$^2$. The permeability after unloading was only 63.5% of that before loading. With the completion of the second and third cycles of loading and unloading experiments, the loading and unloading curves of specimens gradually approached. The elasticity of coal gradually increased. The permeability difference of samples also gradually decreased. After the second cycle, the permeability decreased from $5.07 \times 10^{-16}$ to $4.64 \times 10^{-16}$ m$^2$ with a difference of $0.44 \times 10^{-16}$ m$^2$. After unloading, the permeability was 91.3% of that before loading. After the third cycle, the permeability decreased from $4.64 \times 10^{-16}$ to $4.45 \times 10^{-16}$ m$^2$. The permeability was 91.3% of that before loading.
10^{-16} \text{ m}^2 \text{ with a difference of } 0.19 \times 10^{-16} \text{ m}^2. \text{ After unloading, the permeability was } 95.9\% \text{ of that before loading.}

3. DISCUSSION

3.1. Stress Sensitivity Analysis of Coal Gas Permeability under Different Stress Paths. The variation law of the permeability stress sensitivity coefficient $C_k$ of four coal samples under different stress paths is shown in Figure 7.

It can be seen from Figure 7 that under the conditions of stress paths I and II, the gas permeability stress sensitivity coefficients of coal samples 1# and 2# showed a trend of first decreasing and then increasing with the increase in effective stress. The whole process can be divided into three stages. When the effective stress $\sigma_e$ of samples 1# and 2# was less than 4.5 and 7 MPa, respectively, the permeability stress sensitivity coefficient of the coal sample decreased rapidly with the increase in $\sigma_e$, with a broad variation range. At this time, the coal was rapidly compacted. During the process, the original internal pores and cracks were gradually compressed, showing strong stress sensitivity. When the effective stress $\sigma_e$ was between 4.5−7 and 7−7.84 MPa, the permeability stress sensitivity coefficient of the coal sample decreased slowly with the increase in $\sigma_e$, and the range of change slowed down. At this time, the pores and cracks of the coal were compressed again without the formation of new cracks, and the stress sensitivity was reduced. When the effective stresses were greater than 7 and 7.84 MPa, the permeability stress sensitivity coefficient of the coal sample increased slowly with the increase in $\sigma_e$. It indicated that the coal formed and was destroyed. New pores and cracks generated inside, and the stress sensitivity gradually increased. Under the conditions of stress path III, the gas permeability stress sensitivity coefficient of coal sample 3# showed a gradually increasing trend with the decrease in effective stress $\sigma_e$. The pores and cracks of the coal gradually expanded because of the triaxial pressure relief effect. In the meantime, the stress sensitivity gradually increased and tended to be stabilized. Under the conditions of stress path IV, the average gas permeability stress sensitivity coefficient of coal sample 4# showed an overall decreasing trend with the cyclic loading and unloading of effective stress $\sigma_e$. At this time, the coal is predominated by compaction of pores and cracks. The coal was constantly being compacted, and the stress sensitivity was gradually weakened and stabilized.

3.2. Analysis of the Change Law of the Absolute and Relative Recovery Rate of Coal Gas Permeability and the Difference of Permeability under Stress Path IV. The change law of the absolute and relative recovery rate of coal gas

Figure 7. Variation law of the permeability stress sensitivity coefficient of four coal samples under different stress paths: (a) stress path I; (b) stress path II; (c) stress path III; and (d) stress path IV.
permeability and the difference of permeability under stress path IV is shown in Figure 8.

![Figure 8](https://example.com/f8.png)

**Figure 8.** Relative and absolute recovery rate of gas permeability of coal sample 4# under stress path IV.

It can be seen from Figure 8 that during the three cycles of loading and unloading for coal sample 4#, the permeability of the loading stage and the permeability of the unloading stage both decreased with the increase in the number of cycles. The reduction in permeability during the loading phase was greater than that during the unloading phase. The differences in permeability of each cycle of loading and unloading were also gradually decreased, which were $2.96 \times 10^{-16}$, $0.44 \times 10^{-16}$, and $0.19 \times 10^{-16}$ m$^2$. With the cyclic loading and unloading of axial stress, the relative recovery rate of the specimen showed a gradually increasing trend, while the absolute permeability exhibited a gradually decreasing trend. It indicated that the pores and cracks of the coal specimen under continuous cyclic loading gradually closed and the coal was continuously compacted. As a result, the gas seepage channel was gradually reduced, and the permeability of coal was diminished.

4. FIELD TEST

4.1. Zoning Characteristics of Gas Seepage Capacity for Bottom Coal in the Horizontal Slicing Mining Face of Steeply Inclined and Extra-Thick Coal Seams. Wudong Coal Mine is located in Midong District, Urumqi City, Xinjiang Autonomous Region, China. The gas resources of the mine are relatively rich, concentrated in the east wing of no. 45 coal seam. The horizontal slicing mining face of the east wing for the no. 45 coal seam at +575 m level is currently mined to 480 m, with a dip length of 40 m and a stage height of 25 m. The no. 45 coal seam where the working face is located is a steeply inclined extra-thick coal seam with 45° inclination angle and an average total thickness of 28.47 m. The coal seam gas content is 6.26 m$^3$/t, and the gas pressure is 0.52 MPa. According to the onsite mine pressure monitoring data, the stress recovery zone of coal at the bottom for the working face was located 60 m behind the coal wall of the working face. The stress relief zone was located 5 m in front of the coal wall and 60 m behind the coal wall of the working face. The stress concentration zone was located at 5−40 m in front of the working face. The original stress zone was located 40 m behind the front coal wall of the working face. According to the analysis results of the change law for coal gas permeability under four stress paths, combined with the actually measured stress zone range for the bottom coal of the working face, it can be concluded that the gas permeability of bottom coal for the working face in the horizontal slicing mining face of steeply inclined and extra-thick coal seams also exhibited significant

![Figure 9](https://example.com/f9.png)

**Figure 9.** Zoning characteristics of gas seepage capacity for bottom coal in the horizontal slicing mining face of steeply inclined and extra-thick coal seams.
zoning characteristics. The zoning situation is shown in Figure 9.

It can be seen from Figure 9 that the gas seepage capacity of bottom coal for the horizontal slicing mining face on the east side of the no. 45 coal seam at +575 m level is divided into four zones, namely, seepage reduction zone, seepage sharp increase zone, seepage reduction zone, and original seepage zone. The bottom coal, 60 m behind the coal wall of the working face, is in the seepage reduction zone. In this zone, since the gas seepage velocity of coal is small, the gas is not easy to migrate to the upper slicing mining face or the goaf. A large amount of gas in the zone tends to accumulate. Because the coal in this zone is in the stress recovery zone, under the action of cyclic loading, the coal is continuously compacted. As a result, the internal pores no longer change after the cyclic loading, and the permeability gradually decreases and tends to stabilize. The bottom coal within the range of 5−40 m in front of the coal wall for the working face is the seepage sharp increase zone. The permeability of coal increases sharply in the unloaded state, and a large amount of gas seepage channels are generated at the same time. The bottom high-pressure gas could quickly move the bottom coal to the upper slicing mining face, causing the gas on the working face to exceed the limit. The bottom coal within the range of 5−40 m in front of the coal wall for the working face is the seepage reduction zone. The coal in this zone is in the stress relief zone, and the stress of coal is near the yield strength limit. At this time, although new pores and cracks are generated in some coal bodies, the entirety is still in a state of compression and deformation. A large number of pores and cracks are compressed and closed, and the ability of gas migration in the coal is reduced, resulting in a large amount of gas accumulation in the stress concentration zone of bottom coal. The bottom coal, 40 m in front of the coal wall for the working face, is the original seepage zone. The coal in this zone is far away from the working face and is basically unaffected by mining. The internal pores and the coal gas permeability remain in their original states.

4.2. Test Design and Analysis of the Test Data. To verify the seepage capacity of bottom coal in different stress zones in the horizontal slicing mining face of steeply inclined and extra-thick coal seams. The gas drainage boreholes 1#, 2#, 3#, and 4# were arranged in the original stress zone, stress concentration zone, stress relief zone, and stress recovery zone in the bottom coal of the horizontal slicing mining face at the east side for the no. 45 coal seam at +575 m level, respectively, as shown in Figure 10.

The gas concentration change trend within 60 days of extraction is shown in Figure 11.

It can be seen from Figure 11 that the gas concentration of gas drainage boreholes 1#, 2#, 3#, and 4# gradually decreased and tended to stabilize with the increase in the drainage time. The average gas drainage concentration of four boreholes is in the order borehole 3# > borehole 1# > borehole 2# > borehole 4#, which were 43.07, 27.04, 17.06, and 8.85%, respectively. The average gas drainage concentration of borehole 3# was the highest, mainly because borehole 3# is located in the stress relief zone of the coal at the bottom of the working face. This zone is the seepage sharp increase zone, with more developed pores and cracks. There are a large number of gas seepage channels, and the gas drainage rate is high. The average gas drainage concentration of borehole 4# is the
lowest, mainly because borehole 4# is located in the stress recovery zone of the coal at the bottom of the working face. This zone is the seepage reduction area, and the coal is constantly under the action of cyclic loading. After being compacted, the permeability gradually decreases, which further leads to a reduced gas seepage capacity and a low gas drainage rate. The average gas drainage concentration of borehole 2# in the stress concentration zone of coal at the bottom for the working face is higher than that of borehole 4#, indicating that the gas seepage capacity in the bottom coal stress concentration zone of the horizontal slicing mining face in steeply inclined and extra-thick coal seams is higher than that of the stress recovery zone. In summary, the analysis results of the field test validate the rationality of the laboratory experiment. It indicated the zoning characteristics of gas seepage capacity for bottom coal in the horizontal slicing mining face of the steeply inclined extra-thick coal seams.

5. CONCLUSIONS

Through true triaxial fluid–solid coupling seepage and field gas drainage experiments, the seepage characteristics of gas in different stress zones of the bottom coal in the horizontal slicing mining face of steeply inclined extra-thick coal seams are studied. The following conclusions are obtained:

(1) The permeability of coal gas in the original stress zone of the bottom coal first decreased and then increased under conventional triaxial test conditions, reaching the lowest value of $4.59 \times 10^{-16}$ m$^2$ in the elastic–plastic deformation stage (14–18 MPa). After the yield point (14 MPa), the coal expanded. In the meantime, the gas seepage channel increased, and the permeability characteristics were obviously enhanced. The research results show that the evolution of gas permeability of the bottom coal was closely related to the damage and deformation of the coal.

(2) The gas permeability of coal in the stress concentration zone of the bottom coal first decreased and then increased with the axial pressure loading and the confining pressure unloading. The pores and cracks of overall coal were compacted, and the volume was compressed, which leads to the decrease in the gas flow channel. The gas permeability of coal in the stress relief zone of the bottom coal increased rapidly with the decrease in axial pressure and confining pressure, which irreversibly damages the coal. The pores and cracks were only partially reopened, and the gas seepage channel increased. The coal gas permeability in the stress recovery zone of the bottom coal gradually decreased with the cyclic loading and unloading of the axial pressure and tended to stabilize. The coal was continuously compacted, and the gas seepage capacity was weakened. The research conclusion shows that the stress path has an important influence on the permeability characteristics of gas-containing coal, and different stress paths correspond to different gas permeability characteristics.

(3) The permeability stress sensitivity coefficient of the original stress zone and stress concentration zone of the bottom coal showed a trend of first decreasing and then increasing with the increase in effective stress. When the effective stresses were less than 4.5 and 7 MPa, they showed strong stress sensitivity. When the effective stresses were 7 and 8.4 MPa, the minimum values were 0.009 and 0.012 MPa$^{-1}$, respectively. The permeability stress sensitivity coefficient of the bottom coal stress relief zone gradually increased with the increase in effective stress and tended to stabilize. When the stress was 4 MPa, it reached the peak value of 0.124 MPa$^{-1}$. The permeability stress sensitivity coefficient of the bottom coal stress recovery zone gradually decreased with the increase in effective stress and tended to stabilize. With the cyclic loading and unloading of the axial stress, the relative recovery value of the bottom coal gradually increased. In contrast, the absolute permeability and the permeability difference gradually decreased.

(4) The gas seepage capacity of the bottom coal in the horizontal slicing mining face of steeply inclined extra-thick coal seams can be divided into the original seepage zone, the seepage reduction zone, seepage sharp increase zone, and seepage reduction zone from the original stress zone to the stress recovery zone. The gas seepage capacity in the stress concentration zone of the bottom coal was stronger than that of the stress recovery zone. Through the research results of gas seepage characteristics in different stress zones of bottom coal in steeply inclined and extra-thick coal seams, it can be seen that the gas drainage boreholes should be reasonably
arranged in the seepage sharp increase zone, which can effectively reduce the gas released from the bottom coal to the upper slicing mining face. At the same time, it avoids the problem of gas overrun in the working face.

6. EXPERIMENTAL SECTION

6.1. Sample Characteristics and Preparation. The experimental coal samples were taken from the bottom coal of the horizontal slicing mining face on the east side of the no. 45 coal seam at +575 m level in the northern area of Xinjiang Wudong Coal Mine. Due to the complex geological structure and the interior of coal seams, it is impossible to obtain a massive piece of raw coal samples. Since related research shows that briquette and raw coal specimens have similar mechanical properties and seepage characteristics, briquette specimens are used for experimental research. Through a downhole sampling device, 5 kg of coal samples was drilled in the original stress zone, stress concentration zone, stress relief zone, and stress recovery zone, separately, within 15 m of the bottom in the working face. The samples were sealed in plastic packaging and transported to the laboratory. The sampling location is shown in Figure 12.

Production of briquette specimens: first, the raw coal obtained from the original stress zone, stress concentration zone, stress relief zone, and stress recovery zone of bottom coal was crushed with a crusher. Then, pulverized coal particles with 20−40 mesh (1.25 kg) and 40−80 mesh (1.25 kg) were screened out. The coal powders for two types of particle sizes were added to 0.18 kg of water, stirred uniformly, and then put into the coal-forming mold. A molding pressure of 100 MPa was applied to maintain the pressure for 12 h, and four briquette specimens of 100 mm × 100 mm × 200 mm were made. To prevent pulverized coal particles from polluting the pressure chamber and seepage medium after the briquette specimen was damaged during loading and unloading, a heat-shrink tube was used to wrap the coal sample specimen and the upper and lower pressure heads of the maximum principal stress $\sigma_1$. At the same time, a layer of 704 silicone rubber with a thickness of about 1 mm was applied on the four sides and the upper and lower ends, as shown in Figure 13.

6.2. Experimental Apparatus and Testing Procedure. The true triaxial fluid−solid coupling coal seepage experiment system independently developed by the Shandong University of Science and Technology was used as the experimental equipment. It can realize the experimental research on coal and rock seepage characteristics under conventional triaxial and true triaxial stress conditions. The system consists of a true triaxial pressure chamber, hydraulic servo system, gas seepage system, and monitoring and control system, as shown in Figure 14.

In the experiment, the glued coal sample (100 mm × 100 mm × 200 mm) was first installed into the true triaxial pressure chamber, and the upper pressure head air inlet was connected to the gas duct. Then, the hydraulic servo system was started, and the switch was adjusted according to the designed experimental path to control $\sigma_1$ (0−70 MPa), $\sigma_2$ (0−35 MPa), and $\sigma_3$ (0−10 MPa) to carry out the loading and unloading process of the coal sample. Simultaneously, the gas...
tank pressure-reducing valve and the air intake and bottom exhaust valves of the true triaxial pressure chamber were turned on to inflate with a certain gas pressure. Finally, DH5923 dynamic signal test and analysis software of the monitoring and control systems was used to record the loading and unloading path, displacement, and instantaneous flow rate of the experimental coal sample.

6.3. Experimental Design. In this experiment, the references are the stress changes in the original stress zone, stress concentration zone, stress relief zone, and stress recovery zone generated by the bottom coal after the mining operation of the horizontal slicing mining face on the east side of the no. 45 coal seam at +575 m level. At the same time, considering the limitations of experimental equipment and conditions, we streamlined the stress path of the experiment to simulate the evolution law of gas seepage in the bottom coal caused by the mining of the horizontal slicing mining face in steeply inclined and extra-thick coal seams under real conditions. The stress paths are shown in Figure 15.

1 Original stress zone, stress path I, and conventional triaxial loading: according to the original field stress and gas occurrence of the coal at the bottom of the slicing mining face, at room temperature, the coal unaffected by mining is under hydrostatic pressure. First, the three-dimensional stress $\sigma_1 = \sigma_2 = \sigma_3$ to the initial predetermined pressure 4 MPa was applied synchronously to sample 1# through the tracking mode. Then, with a constant three-dimensional stress, 0.52 MPa gas with a concentration of 99.9% was introduced through an inlet. After the gas adsorption reached equilibrium, $\sigma_2 = \sigma_3 = 4$ MPa remained constant, and axial stress $\sigma_1$ was continuously applied at a rate of 0.1 mm/min until the specimen was destroyed.

2 Stress concentration zone, stress path II, and axial pressure loading and confining pressure unloading: first, the three-dimensional stress $\sigma_1 = \sigma_2 = \sigma_3$ to the initial predetermined pressure 4 MPa was applied synchronously to specimen 2# through the tracking mode. The three-dimensional stress was continuously applied until the stresses $\sigma_1$, $\sigma_2$, and $\sigma_3$ were 6, 8, and 6 MPa, respectively. Then, with a constant three-dimensional stress, 0.52 MPa gas with a concentration of 99.9% was introduced through an inlet. After the gas adsorption reached equilibrium, $\sigma_2$ and $\sigma_3$ were increased to 8 and 6 MPa, respectively. Under the conditions of the three-dimensional stress constant, simultaneously, the axial stress $\sigma_1$ was increased at a rate of 0.1 mm/min until the specimen was destroyed.

3 Stress relief zone, stress path III, unloading of axial pressure and confining pressure at the same time: first, the three-dimensional stress $\sigma_1 = \sigma_2 = \sigma_3$ to the initial predetermined pressure 4 MPa was applied synchronously to specimen 3# in the tracking mode. Then, the axial stresses $\sigma_1$ to $\sigma_u$ (80% of peak strength) were applied continuously until the confining pressures $\sigma_2$ and $\sigma_3$ were increased to 8 and 6 MPa, respectively. Under the conditions of the three-dimensional stress constant,
0.52 MPa gas with a concentration of 99.9% was introduced through an inlet. After the gas adsorption reached equilibrium, the experiment was terminated after unloading $\sigma_0$, $\sigma_n$, and $\sigma_1$ at the rates of 0.1, 0.08, and 0.05 mm/min, respectively, to 4 MPa.

4 Stress recovery zone, stress path IV, constant confining pressure, and axial pressure cycle loading and unloading three times: first, the three-dimensional stress $\sigma_1 = \sigma_2 = \sigma_3$ to the initial predetermined pressure 4 MPa was applied synchronously to specimen 4# in the tracking mode. Then, with a constant three-dimensional stress, 0.52 MPa gas with a concentration of 99.9% was introduced through an inlet. After the gas adsorption reached equilibrium, $\sigma_2 = \sigma_3 = 4$ MPa remained constant, and the axial stresses $\sigma_1$ to $\sigma_n$ (80% of peak strength) were increased at a rate of 0.1 mm/min and then unloaded to 4 MPa. After completing three cycles, the experiment was terminated.

It is assumed that the gas seepage process in the experiment is regarded as an isothermal process. The formed coal can be regarded as an isotropic homogeneous material, and the gas seepage in the coal conforms to Darcy’s law. Therefore, the permeability can be calculated according to eq 1\textsuperscript{26}:

$$k = \frac{2q_{fl}L}{A(P_f^2 - P_i^2)}$$

(1)

where $k$ is the permeability, m$^2$; $q$ is the gas flow rate, m$^3$/s; $\mu$ is the dynamic viscosity coefficient of methane, MPa·s; $L$ is the length of the briquette specimen, m; $P_0$ is the atmospheric pressure of the experimental environment, MPa; $A$ is the cross-sectional area, m$^2$; and $P_1$ and $P_2$ are the inlet and outlet gas pressure, respectively, MPa. The parameter values are as follows: $\mu = 1.108 \times 10^{-11}$ MPa·s; $L = 0.2$ m; $P_0 = P_1 = 0.52$ MPa; $A = 0.1 \times 0.1 = 0.01$ m$^2$; and $P_2 = 0.52$ MPa.

The stress sensitivity coefficient $C_k$ of coal gas permeability can be calculated by formula 2\textsuperscript{26}:

$$C_k = \frac{1 - k_1}{k_1} \frac{\Delta k}{\Delta \sigma_1}$$

(2)

where $k_1$ is the permeability under initial stress, m$^2$; $\Delta k$ is the difference in permeability corresponding to the effective stress of two adjacent points, m$^2$; and $\Delta \sigma_1$ is the difference in effective stress between two adjacent points, MPa.

The absolute recovery rate $A_k$ and relative recovery rate $R_k$ of coal gas permeability can be calculated by formulas 3 and 4\textsuperscript{26}:

$$A_k = k_n/k_1$$

(3)

$$R_k = k_{n+1}/k_n$$

(4)

where $k_1$ and $k_{n+1}$ refer to the permeability when the axial stress is unloaded to the lowest point during the $n$ and $n+1$ cycles of loading and unloading, 10$^{-16}$ m$^2$.

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