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ORIGINAL PAPER

Entry Deformation Law in the Full Life Cycle Under Entry Retaining with Roof Cutting

Xingen Ma · Manchao He · Jing Guo · Chongxiao Zhang

Abstract   In roof cutting pressure releasing gob-side entry retaining (RCPRGER) technology, the full life cycle of the retained entry includes two main parts: the entry retaining and retained entry reuse. The existing studies all focus on the process of entry retaining, while the studies of the whole life cycle and reuse process are relatively deficient. To compensate for the deficiency in the existing research and explore the deformation law of the entry in the whole life cycle under entry retaining with roof cutting, this paper takes the 8304 and 8305 working faces of the Tashan Coal Mine as an example, and the entry deformation evolution in the retaining and reuse processes is studied. First, this paper summarizes the technological process of RCPRGER and reuse and then deduces the stress evolution process of entry surrounding rocks, specifically including the analysis of the roof cutting short beam structure model. Subsequently, the monitoring schemes of the entry deformation and mine pressure in the working face within the retaining and reuse processes are proposed. Finally, through the practical examples of test working faces, it is found that the two entry sides move symmetrically between the upper and lower parts. The main deformation in the early stage of the entry retaining is the displacement of the gangue wall, and the main deformation in the later stage and reuse stage is the displacement of the coal wall. The roof and floor move asymmetrically between the left and right parts, the deformation of the roof cutting side is larger at each stage, and the roof subsidence is the main source of deformation.

Keywords   Entry deformation law · Full life cycle · Roof cutting and pressure releasing · Gob-side entry retaining · Retained entry reuse

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1 Introduction

Sustainable development is the common choice for human economic and social development in the world (Lu et al. 2016). Sustainable development is not only directly related to human survival at present but also

indirectly affects human development in the future (Ali-Toudert and Ji 2017). At present, coal is the main basic energy source for human production activities, and its efficient mining and utilization have become the common choice of all countries around the world (Hebblew and Lu 2004).

Compared with the traditional long wall mining method with section coal pillars, the gob-side entry retaining technology can realize effective coal mining without leaving behind section coal pillars (Wilson 1975; Hongbin and Aiguo 2004). Therefore, under the current energy situation of the increasing shortage of coal resources, this technology, which can greatly improve the field recovery rate of coal resources, has a very high research and promotion value (Zhang et al. 2017; Wang and Wang 2012). However, in previous studies, the problems of goaf filling and retained entry support in the process of entry retaining have not been solved well. While realizing coal mining without section coal pillars, a higher price is often paid with regards to the aspects of goaf backfilling, reinforcing support, entry repair and so on (Siriwardane et al. 2003; Li 2018; Zhang et al. 2018).

Based on these phenomena, He Manchao put forward the roof cutting pressure releasing gob-side entry retaining (RCPRGER) technology in 2008 (He et al. 2017). Thus, through the roof presplitting cutting along the advancing direction of the working face on the entry roof, the horizontal stress transfer between the goaf roof and entry roof is cut off to a certain extent, then after mining the first working face, the goaf roof collapses and fills up the space near the retained entry through bulking, which can achieve a high mining efficiency with no coal pillars and no additional filling materials required (He et al. 2018a). Through various developments in recent years, this new technology has been successfully tested under different strata conditions in many mines, such as: Zhang Guofeng carried out roof cutting entry retaining test in the Baijiao Coal Mine of the Sichuan Coal Group successfully, and preliminarily established the roof cutting entry retaining technology system under the condition of composite roof medium thick coal seam (Zhang et al. 2011); Guo Zhibiao used the 3118 working face of the Jiayang Coal Mine as an example and studied the design method of the key parameters of roof cutting under thin coal seam condition (Guo et al. 2016); Yang Xiaojie explored the supporting principle and application design of constant resistance anchor

cable (CRAC), based on which the RCPRGER technology was applied under deep buried broken roof condition (Yang et al. 2017).

It can be seen that the existing research on the RCPRGER technology focuses on the entry retaining process, including the design of key parameters and entry supporting roof cutting, while research on the reuse process of the retained entry is relatively lacking. However, under the roof cutting entry retaining technology, the entire life cycle of the entry includes two parts: the entry retaining and entry reuse, and the entry support should also be designed appropriately according to these two parts. Therefore, to explore the deformation law within the whole life cycle of the retained entry under the roof cutting entry retaining technology, to make up for the deficiencies in the existing research, and to provide an effective reference for the entry support design and technical popularization of this technology, this paper employs the 8304 and 8305 working faces of the Tashan Coal Mine as examples to analyze and study the deformation evolution of the entry in the whole life cycle of the entry retaining and reuse processes.

2 Research Background

To study the entry deformation law in the whole life cycle under the roof cutting entry retaining, the 8304 and 8305 working faces of the Tashan Coal Mine are used as engineering examples to study the entry deformation evolution within the entry retaining and reuse processes.

2.1 Project Overview

From the layout plan as shown in Fig. 1a, the 8304 working face (a strike length of 670 m and tendency length of 127 m) of the Tashan Coal Mine is the first mining face on panel 3 of the mine and is adjacent to the 8305 working face (a strike length of 680 m and a tendency length of 110 m). The coal seam thickness in the working face area is 1.80–3.55 m, with an average thickness of 3.1 m. The immediate roof and floor are all mudstone, and the main roof and floor are fine sandstone and siltstone, respectively. The ground elevation ranges from 1391.4 to 1417.7 m, the working face elevation ranges from 1006.3 to 1024.2 m, and the burial depth is approximately 367–411 m. The
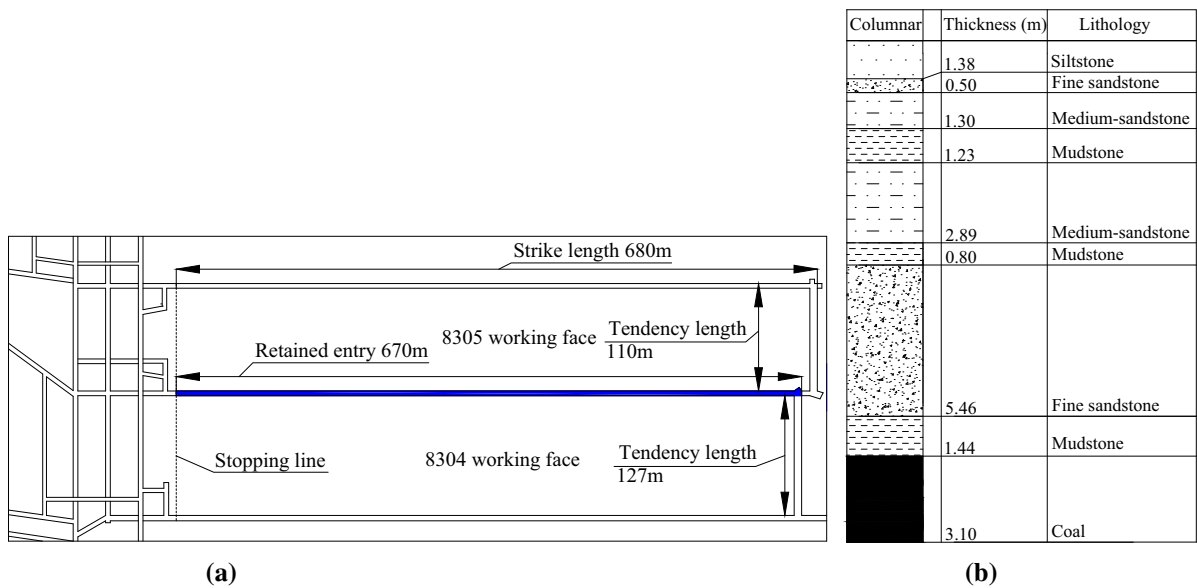
Columnar	Thickness (m)	Lithology
	1.38	Siltstone
	0.50	Fine sandstone
	1.30	Medium-sandstone
	1.23	Mudstone
	2.89	Medium-sandstone
	0.80	Mudstone
	5.46	Fine sandstone
	1.44	Mudstone
	3.10	Coal

Fig. 1 Layout and roof lithology of the 8304 and 8305 working faces: **a** layout of the working faces; **b** lithological profile

dip angle of the coal seam is between 2° and 6°, and the average is 4°. The lithological column of the roof is shown in Fig. 1b (Ma et al. 2017).

The comprehensive mechanized mining method is adopted in the test working faces. The mining of the 8304 working face began on December 1, 2017, and ended on April 14, 2018. The maximum daily mining speed was 13.0 m/day, and the average daily mining speed was 5.0 m/day. During the mining period, the head entry of the working face acted as a transportation lane, and the tail entry acted as a pedestrian lane. Between the two lanes, the tail entry was used to carry out the RCPRGER. After the completion of mining and entry retaining of the 8304 working face, mining of the 8305 working face began on June 9, 2018, and ended on October 28, 2018. The maximum daily mining speed was 12.0 m/day, while the average daily mining speed was 4.7 m/day. The head entry of the working face was still used as a transportation lane, the retained entry of the 8304 working face was used as the tail entry for pedestrians, and the mining process of the 8305 working face was also the process of the retained entry reuse.

2.2 Whole Life Cycle of the Retained Entry

The entry retaining process of the 8304 working face and the retained entry reuse process of the 8305

working face are shown in Fig. 2 (Sun et al. 2014; Yang et al. 2015; Archibald et al. 1999). The stages dividing the retained entry in the whole life cycle and analysis of the structure of the rocks surrounding the entry could provide some reference for the subsequent entry deformation analysis and the entry support design. The whole life cycle of the retained entry mainly consisted of two stages (as shown in Fig. 2a): one was the roof cutting entry retaining process with mining of the 8304 working face, and the other was the retained entry reuse process with mining of the 8305 working face. In the entire life cycle of the retained entry, there were three main surrounding rock structure types in the inclined section of the entry (as shown in Fig. 2b). Section A–A shows the rock structure surrounding the entry before mining of the 8304 and 8305 working faces; the entry should be excavated first, the roof support should be reinforced with anchor cables and roof presplitting cutting should be carried out. Section B-B shows that after mining of the 8304 working face, the goaf roof on one side of the retained entry collapsed along the roof cutting slit, and the gangue filled up the goaf space near the retained entry. At the same time, the gangue wall that was maintaining the support should also be established in a timely manner to promote the formation of the gangue wall and complete the entry retaining. Section C–C shows that after mining of the 8305 working face, the reuse of
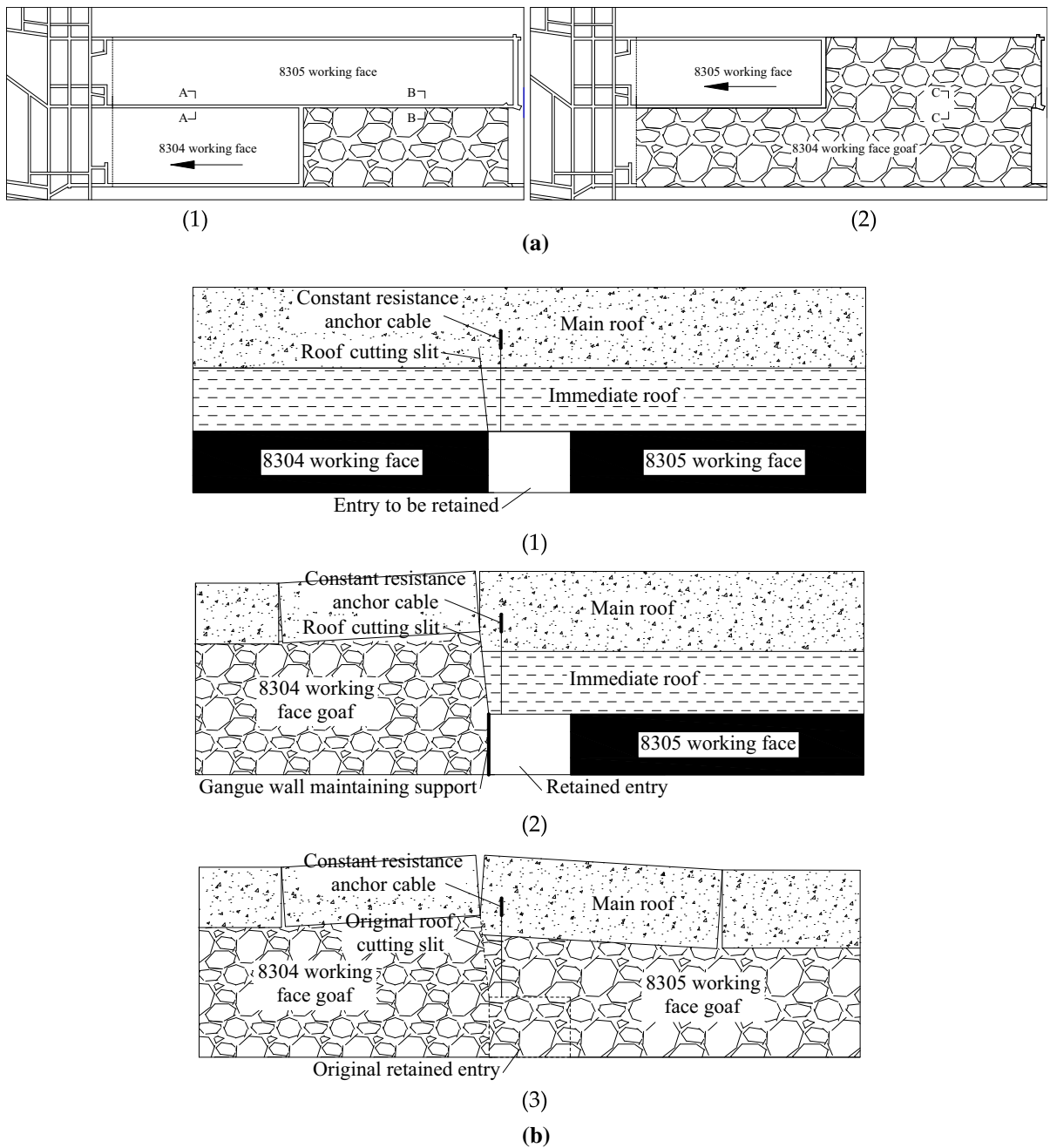
Fig. 2 Retained entry whole life cycle: **a** entry retaining and reuse plan: (1) roof cutting entry retaining process with mining of the 8304 working face; (2) retained entry reuse process with mining of the 8305 working face; **b** Entry retaining and reuse section: (1) section A–A; (2) section B–B; (3) section C–C

the retained entry had been completed. At the end of the reuse process, the gangue wall that was maintaining the support and the anchor cable lock should be removed to promote collapse of the goaf of the 8305

working face. The gangue accumulation on the roof cutting side of the original retained entry was denser due to the roof cutting and gangue wall that was maintaining the support, so the gangue around that

area could support the overburden better, resulting in a smaller subsidence of the main roof that was within a certain range.

3 Analysis of the Roadway Deformation Mechanism

3.1 Stress Development Process in the Surrounding Rock

Based on the above analysis of the entry retaining and reuse processes, the stress development process of the rocks surrounding the entry can be summarized. Taking point A as an example, which is located on the goaf roof of the first mining face close to the roof cutting slit, the stress evolution during gob-side entry retaining has been summarized based on the Mohr stress circle theory in existing research (Ma et al. 2018a). On this basis, the stresses change in remining stress state is shown in Fig. 3.

At first, before the entry excavation, point A is in the original rock stress state and subjected to three principal stresses of σ_1^0, σ_2^0 and σ_3^0, which are the maximum principal stress, intermediate principal stress and minimum principal stress ($\sigma_1^0 > \sigma_2^0 > \sigma_3^0$), respectively. Then, the normal stress σ and shear stress τ in any direction of point A can be expressed as follows (Jaeger and Cook 1969; Stankus and Peng 1994; Shabanimashcool and Li 2012):

$$\begin{cases} \sigma = \dfrac{1}{2}(\sigma_1^0 + \sigma_3^0) + \dfrac{1}{2}(\sigma_1^0 - \sigma_3^0)\cos 2\theta \\ \tau = \dfrac{1}{2}(\sigma_1^0 - \sigma_3^0)\sin 2\theta \end{cases}, \quad (1)$$

where θ is the angle between σ and the maximum principal stress. The strength envelope curve can be approximately expressed as:

$$\tau = c + \sigma \tan \varphi, \quad (2)$$

where c and ϕ are the cohesive force and internal friction angle of the rock, respectively.

When the entry excavation stress state, anchor cable support stress state, roof cutting stress state, premining stress state and postmining stress state have been gone through, the mining of the first working face is completed, the entry is also retained; then, the mining of the adjacent working face begins with the reuse of the retained entry, and the stress state of the retained entry turns into the remining stress state. In this process, point A will be affected by the prestress concentration of remining first, then the working face roof will collapse, and the stress state at point A will be further increased. During the remining process, the main stress change at point A is the further increase in the principal stress, namely, σ_1^5 increases to σ_1^6.

In summary, the stress evolution process in the whole life cycle of the surrounding rock of the retained entry can be divided into seven stages: original rock stress state, entry excavation stress state, anchor cable support stress state, roof cutting stress state, premining stress state, postmining stress state and remining stress state. Among them, the first three stress evolution stages occur before the roof cutting and are not affected by the roof cutting slit; the latter three stress evolution stages are key to whether the roof of the goaf can be completely separated from the roof of the retained roadway and collapse smoothly after the roof cutting, which directly affects the effect of the retained entry and the last retained entry reuse process.

3.2 Deformation Mechanism of the Retained Entry

Through the analysis in Sect. 2.1, it can be seen that in the roof cutting entry retaining technology, the roof cutting short beam structure is the key factor affecting the retained entry deformation. To study the deformation mechanism under this structural condition, this
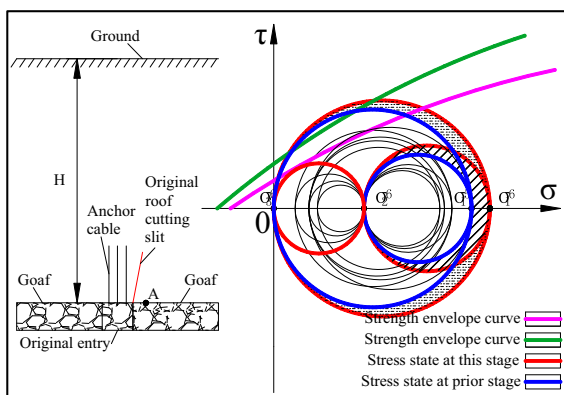

Fig. 3 Remining stress state

section employs the short beam structure to carry out mechanical modeling and analysis.

The working face is usually long under long wall mining and the analysis emphasis is the working face tendency direction in this study, so a simplified mechanical model of the roof cutting short beam structure is shown in Fig. 4, and the gangue wall and coal wall on each side of the retained entry support the overlying strata (Xu et al. 2015; Ma et al. 2018b; Vakili and Hebblewhite 2010). In Fig. 4, q is the average load caused by the basic roof weight and the load of the upper rock mass; q_0 is the average load of the direct roof weight; F_1 is the resultant force of all supports in the roadway; a is the width of the roadway; b is the distance between F_1 and the coal wall; T_A is the horizontal thrust in rock A; N_A is the shear force of rock A; M_A is the bending moment in rock A at point A'; T_B, N_B and M_B have the same meaning as T_A, N_A and M_A, but with regards to rock B; M_0 is the limit of the bending moment of the direct roof; x_0 is the lateral width of the limit of the equilibrium area in the coal wall; σ is the support of the coal wall plastic zone; and F_2 is the support of the gangue wall. Under this structure, F_2 is small when the gangue wall is instable, and F_2 is approximately 0 in a certain area close to the working face. Based on the latter and the XY coordinates in Fig. 4, the roadway roof can be regarded as a cantilever beam mechanical model, and the equation of the deflection curve is obtained as follows:

$$y = -\frac{(q + q_0)x^2}{24EI}(x^2 - 4ax + 6a^2). \tag{3}$$

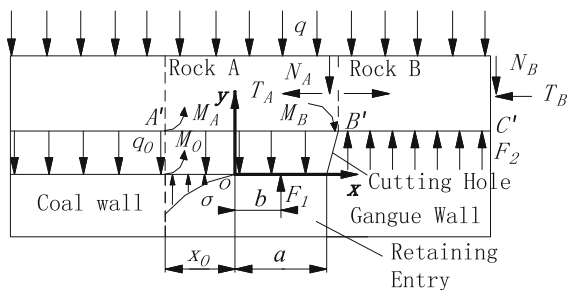where y is equal to the maximum deflection when $x = a$, and its absolute value is:

Fig. 4 Simplified mechanical model of the roof cutting short beam

$$|y|_{max} = \frac{(q + q_0)a^4}{8EI}. \tag{4}$$

The roof support under this structure is mainly realized by single hydraulic props (lagging temporary support). To determine F_1 can be solved as follow (Hou and Ma 1989):

$$\begin{aligned}
F_1 = [&M_B(L + x_0 + a) + q(x_0 + a)^2/2 \\
&+ qL(x_0 + a)/2 + q_0(x_0 + a)^2/2 \\
&+ q(x_0 + a)/2 - M_A - M_0 - qL/4 \\
&- \int_0^{x_0} \sigma(x_0 - x)dx]/(x_0 + b).
\end{aligned} \tag{5}$$

where L is the lateral breaking span of the basic roof.

According to Eq. (3), under this structure, the deformation on the roof cutting side of the entry roof is the largest, so the support in the roadway should be more concentrated on the roof cutting side. In addition, according to Eq. (5), the entry support demand is directly related to the support ability of the gangue wall. Therefore, under the same entry support conditions, the roof subsidence on the roof cutting side of the retained entry will be larger than that of the uncut side of the roof, and the deformation extent of the retained entry is related to the condition of the surrounding rocks and the density of the gangue wall.

4 Monitoring Scheme of the Entry Retaining and Reuse

On the basis of mastering the stress evolution process of the surrounding rock of the entry in the processes of roof cutting of the entry retaining and reuse and the deformation mechanism of the roof cutting short beam, the 8304 and 8305 working faces are taken as engineering examples to further explore the retained entry deformation law in the whole life cycle by field monitoring.

In the test of the RCPRGER method in the Tashan Coal Mine, the main supporting materials used were steel bolt, steel anchor cable, CRAC, and single hydraulic prop. The steel bolt specification is ϕ 22 mm × 2500 mm, the installed anchorage force should not be less than 8 t, and the pretightening force should not be less than 200 Nm. The specification of the steel anchor cable and CRAC is ϕ 21.8 mm × 9000 mm, the installed anchorage force should not be

less than 40 t, and the pretightening force should not be less than 25 t. The type of single hydraulic prop used is DN35-160/90, the maximum support height is 3500 mm, the rated working resistance is 16 t, and the initial support force should not be less than 9 t. Among them, the CRAC used is the HZS35-300 type, which is designed by He Manchao; its maximum allowable deformation is 350 mm, and the constant resistance is 30 ± 2 t. In addition, according to the roof lithology and mining height, to fill the goaf near the retained entry effectively with gangue material when the roof of the first mining face collapses, the roof cutting height is designed to be 7.7 m; in order to lower the friction effect on the roof cutting surface when the goaf roof of the first mining face collapses and to avoid the presplitting blasting of roof cutting destroying the entry anchor cable support, the roof

cutting angle is designed to be 15° from the vertical to the goaf (Ma et al. 2018c). Furthermore, the advancing temporary support and lagging temporary support of retained entry are designed according to past field experience (Alejano et al. 1999; Wang et al. 2016; He et al. 2018b).

4.1 Entry Deformation Monitoring

Four plans for entry deformation monitoring were designed, as shown in Fig. 5. Plan 1 involved measurement of the length changes in the four segments AC, BD, EG and FH to judge whether the entry deformation is symmetrical. If the convergence between roof and floor was asymmetrical between the left and right parts as indicated by the measurement results of plan 1, that is, the change trend or magnitude
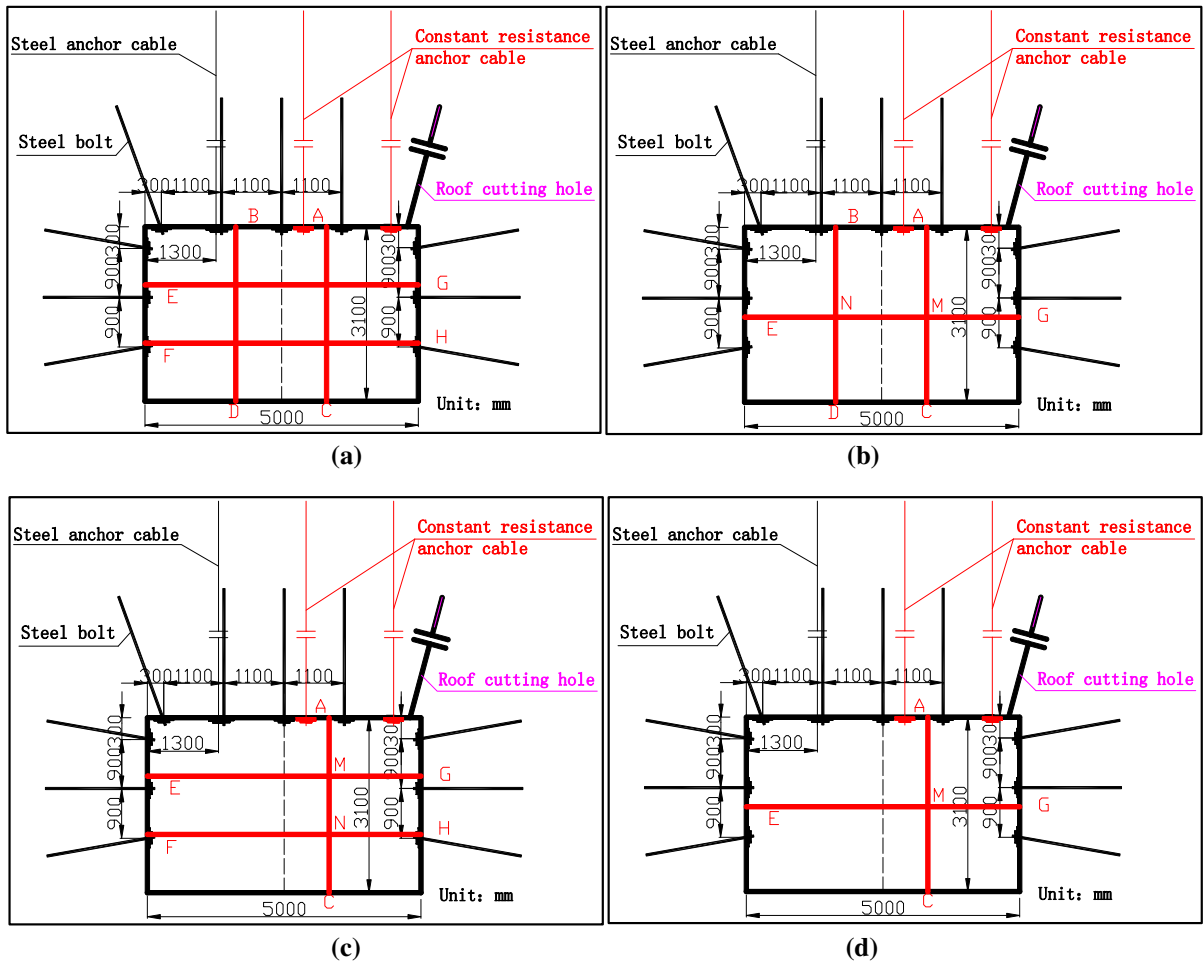

Fig. 5 Four plans for entry deformation monitoring: **a** plan 1; **b** plan 2; **c** plan 3; **d** plan 4

of the AC and BD segments were obviously different, then plan 2 was carried out for the subsequent monitoring; in plan B the length changes in the four segments AM, MC, BN and ND needed to be measured to determine the main source of the asymmetric convergence between the roof and floor. If the convergence between the two walls was asymmetrical between the upper and lower parts as indicated by the measurement results of plan 1, that is, the change trend or magnitude of the EG and FH segments were obviously different, then plan 3 was used to carry out follow-up monitoring, in which the length changes in the four segments EM, MG, FN and NH needed to be measured to determine the main source of the asymmetric convergence between the two walls. When the deformation trend and the source of the asymmetric deformation were determined by plan 2 or plan 3, plan 4 was used to further monitor the four segments AM, MC, EM and MG to determine the specific degree of entry deformation and the proportion of each source.

Through the deformation analysis in Sect. 2.2, it can be seen that the entry deformation on the roof cutting side should be relatively serious under the roof cutting short beam structure, so the convergence between the roof and floor was measured on the roof cutting side in plan 4. The two sides of the entry usually experienced the largest shrinkage in the middle, which was the key restriction on the passage of personnel and equipment, and thus the convergence between the two walls was measured in the middle (plan 4). Combined with the field conditions of the 8304 and 8305 working faces, plan 1 was adopted to monitor the first 200 m section of the retained entry when the 8304 working face and entry retaining were mined. Then, according to the monitoring results, either plan 2 or 3 were selected for the monitoring the middle 200 m section of the retained entry. The last 270 m section and the retained entry reuse process were monitored with plan 4. The entry deformation monitoring range when the 8304 working face was mined included the advancing temporary support section and the retained entry section behind the working face, while the monitoring range when the 8305 working face was mined only involved the advancing temporary support section. In addition, the deflection angle of the roof, floor or two sides could be calculated from the above monitoring results. Taking the roof deformation as an example, the deflection

angle of the roof can be calculated according to the following formula:

$$\theta = \arctan \frac{L'_{AM} - L'_{BN}}{L_{AB}}, \qquad (6)$$

where L'_{AM} is the shortening of segment AM; L'_{BN} is the shortening of segment BN; and L_{AB} is the horizontal distance between points A and B.

4.2 Weighting Monitoring of the Working Face

While monitoring the entry deformation, the working resistances of the hydraulic supports in the working face were also monitored. The reasons are as follows: (1) the end support of the working face not only undertakes the support task of the entry near the working face but also reflects the stress situation of the entry nearby; (2) in the theoretical system of the roof cutting short beam, the goaf roof of the first mining working face can collapse to fill the goaf space near the retained entry and support the overburden; then, the weighting strength of the working face will be weakened. Therefore, monitoring the working resistances of the hydraulic supports could provide references to judge the collapse situation of the goaf roof and guide the design of the entry reinforcement support.

The weighting monitoring scheme of the working face is shown in Fig. 6. In the 8304 working face, the working resistance of the hydraulic supports whose serial numbers are 1, 6, 12, 23, 34, 45, 62, 68, and 73 were monitored to explore the working face weighting law with roof cutting entry retaining and the lateral influence area in the first working face by roof cutting pressure releasing. In the 8305 working face, the working resistance of the hydraulic supports whose serial numbers are 1, 6, 11, 16, 24, 33, 42, 50, 55, 60, and 65 were monitored to explore the working face weighting law with retained entry reuse and the reverse lateral influence area in the second working face by roof cutting pressure releasing.

5 Law Analysis of the Entry Deformation

5.1 The Whole Process Analysis of the Retained Entry Deformation

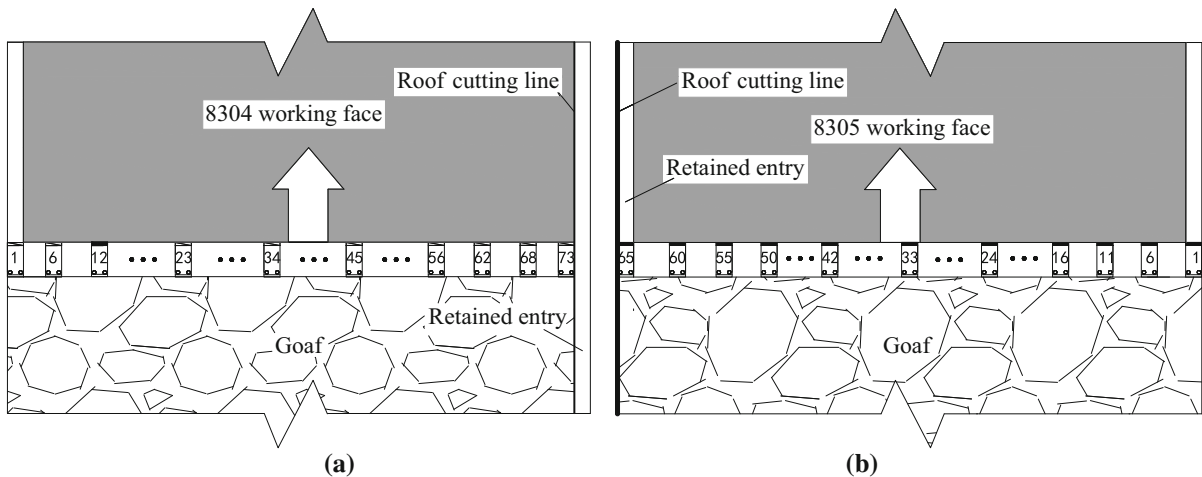The retained entry of the 8304 working face was divided into three sections for the entry deformation

Fig. 6 Weighting monitoring scheme on working face: **a** monitoring scheme of 8304 working face; **b** monitoring scheme of 8305 working face

monitoring: the first 200 m section (footage of 0–200 m), the middle 200 m section (footage of 200–400 m), and the last 270 m section (footage of 400–670 m). The typical entry retaining field effects of the three entry sections are shown in Fig. 7.

In the process of mining the 8304 working face and entry retaining, the retained entry deformation monitoring of the first 200 m section was carried out with plan 1, as shown in Sect. 3.1, and the monitoring results are shown in Fig. 8.

According to the monitoring results of the first 200 m section, it can be seen that: (1) the change trend and extent of the two sides between the upper and lower parts were the same. At a footage of 0 m, the final convergence of the two sides was 125 and 119 mm in the upper and lower parts, respectively. At a footage of 100 m, the final convergence of the two sides was 220 mm in both the upper and lower parts. (2) The change trend of the roof and floor was the same between the left and right parts, while the extents of the change were different; the value was larger on the roof cutting side. At a footage of 0 m, the final convergence of the roof and floor was 203 mm on the roof cutting side and 182 mm on the coal wall side. At a footage of 100 m, the final convergence of the roof and floor was 273 mm on the roof cutting side and 230 mm on the coal wall side. (3) The retained entry tended to be stable when it was behind the working face at a distance of approximately 200 m. At a footage of 0 m, the roof and floor approachings tended to be stable at a distance of 201 m behind the working

face, and the lagging temporary support was withdrawn at 270 m behind the working face. At a footage of 100 m, the roof and floor approachings tended to be stable at 207 m behind the working face, and the lagging of the temporary support was withdrawn at 245 m behind the working face. (4) Affected by the coal wall behind the open-off cut, the retained entry overall deformation was smaller at a footage of 0 m compared to at a footage of 100 m.

The monitoring results of the first 200 m section show that the deformation laws of the two entry sides were the same between the upper and lower parts of the retained entry. Therefore, the middle 200 m section of the retained entry was monitored with plan 2, and the monitoring focus was the convergence between the roof and floor. The monitoring results are shown in Fig. 9.

According to the monitoring results of the middle 200 m section, it can be seen that: (1) The deformation of the floor heave was more or less the same between the roof cutting side and the coal wall side, the maximum deformation value was 102 mm, and the floor stable zone was behind the working face by more than 195 m. (2) The roof subsidence change trend of the two sides was the same, while the extents of the change were different. The roof stable zone was behind the working face at a distance of more than 230 m, but the final roof subsidence was 325 mm on the roof cutting side and 260 mm on the coal wall side. As the main source of the convergence between the roof and floor, in addition to the roof subsidence, the
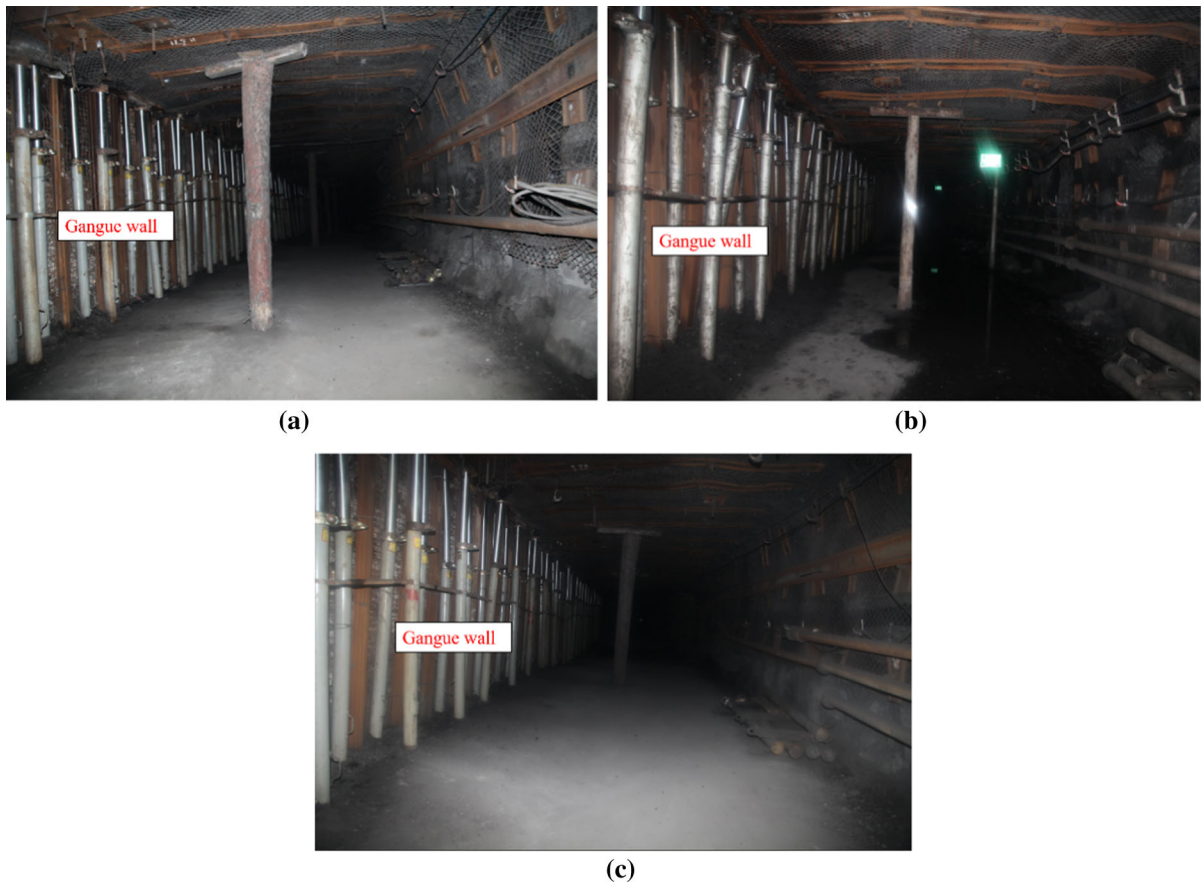
Fig. 7 Field effects of the entry retaining: **a** footage of 100 m; **b** footage of 300 m; **c** footage of 500 m

final deflection angle of the roof was 1.3°, as calculated by Eq. (6). (3) Compared with the monitoring results of the first 200 m section, the convergence deformation of the roof and floor was more severe in the middle 200 m section.

The last 270 m section was monitored with plan 4, and the convergence law between two entry sides was the monitoring focus. The monitoring results are shown in Fig. 10.

According to the monitoring results of the last 270 m section, it can be seen that: (1) In the early stage, the convergence of the two walls of the entry mainly involved the deformation of the gangue wall, and in the later stage, the convergence mainly exhibited the deformation of the coal wall. At a footage of 400 m, the final approaching of the gangue wall was 63 mm, and the final approaching of the coal wall was 127 mm. (2) The overall extent of the deformation of this area was less compared to the first

200 m section and middle 200 m section. In addition to the convergence of the two walls mentioned above, the final floor heave was 88 mm, and the final roof subsidence was 173 mm.

During the mining period of the 8305 working face and retained entry reuse, the entry deformation was monitored in the advancing temporary support section (within an advancing distance of 30 m of the working face) with plan 4. To compare the entry deformation in the entry retaining process, the 400 m footage of the retained entry was still selected for monitoring, and the monitoring results are shown in Fig. 11.

According to the monitoring results, it can be seen that: (1) When the mining face reaches a footage of 400 m, the convergence of the roof and floor at this entry section reached 12.5 mm, while the roof subsidence was 9.7 mm and the floor heave was 2.8 mm. Compared with the period of entry retaining, the deformation of the roof and floor in this stage was
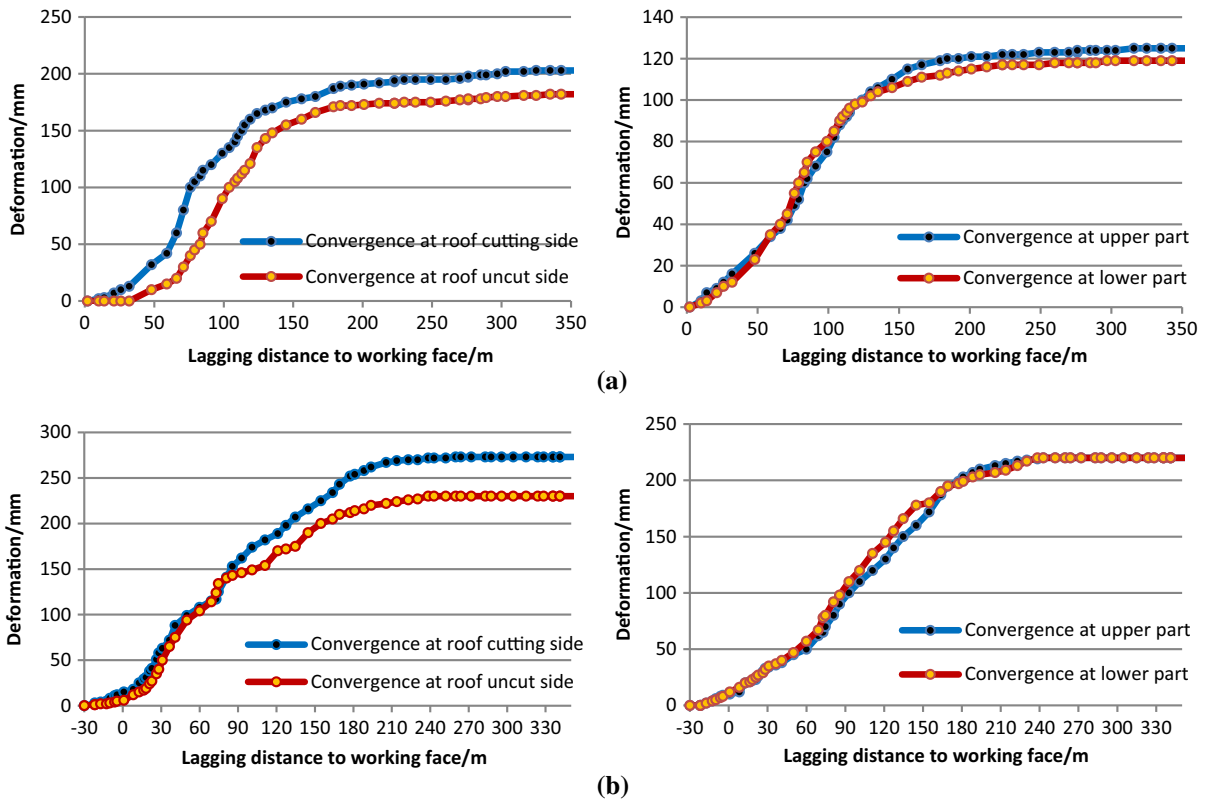
Fig. 8 Retained entry deformation monitoring of the first 200 m section: **a** footage of 0 m; **b** footage of 100 m
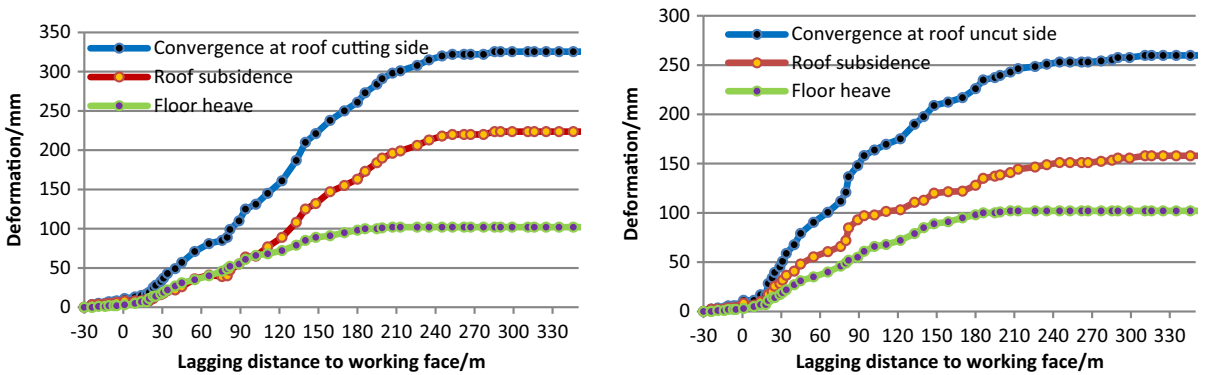

Fig. 9 Retained entry deformation monitoring of the middle 200 m section (footage of 300 m)

slightly larger, but the roof subsidence was still the main form of deformation. (2) Furthermore, the convergence of the two walls reached 14.5 mm, while the coal wall approaching was 8.4 mm and the gangue wall approaching was 6.1 mm. Compared with the period of entry retaining, the deformation of the two walls was also slightly more profound, and the coal

wall approaching was the main location of the deformation.

5.2 Analysis of the Mine Pressure on the Working Face

To analyze the effect of roof cutting pressure releasing under entry retaining process, the monitoring data of
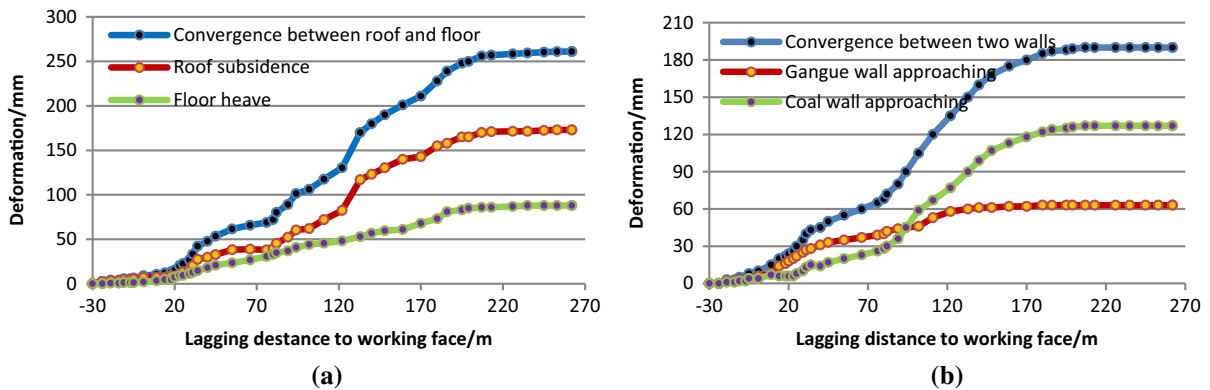
Fig. 10 Retained entry deformation monitoring of last 270 m section (footage 400 m): **a** convergence between roof and floor; **b** convergence between two walls
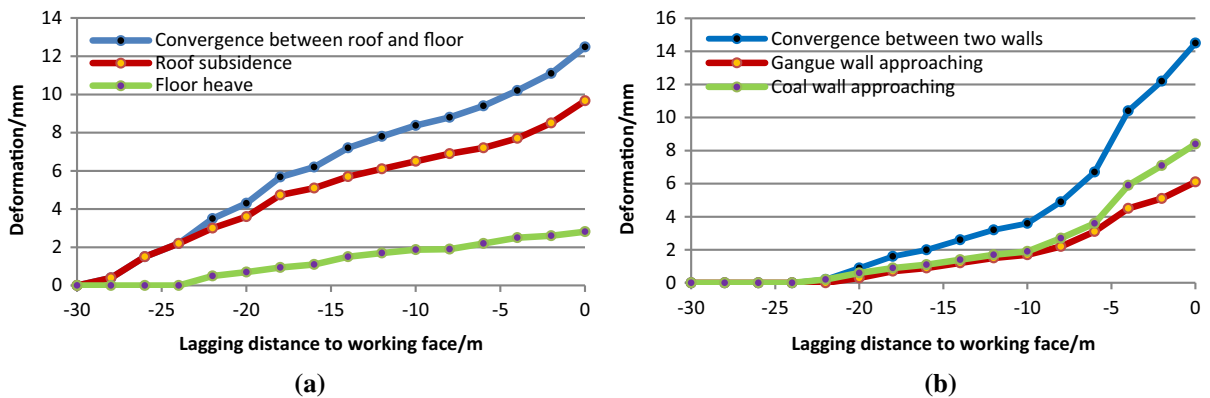

Fig. 11 Entry deformation monitoring during the reuse process (footage of 400 m): **a** convergence between the roof and floor; **b** convergence between the two walls

the working resistance of the hydraulic support in 8304 working face have been analyzed (He et al. 2018a, b). The distributions of the weighting step and strength were asymmetrical due to the influence of the entry retaining roof cutting. The periodic weighting step of the roof cutting side was longer than that of the uncut side of the roof, and the weighting strength was weaker than that of the uncut side of the roof. After the #5 support, the roof cutting effect became notable, namely, the lateral influence range on the working face by roof cutting was approximately 29.75 m (the width of a single hydraulic support was 1.75 m), and the closer the roof cutting line was to the roof cutting line, the more obvious the pressure releasing effect became. The entry retaining roof cutting had a larger influence on the peak weighting strength of the hydraulic support compared to the average weighting strength. Specifically, compared with the uncut side of the roof,

on the roof cutting side of the 8304 working face, the pressure release ratio of the peak weighting strength was 25.0% and the average weighting strength was 9.2%. The increase in the periodic weighting step indicates that under the influence of roof cutting blasting, the roof collapse height was larger and the gangue lumpiness was smaller in the area affected by roof cutting (the bulking coefficient was larger). Then, in this area, the goaf could be filled effectively, and the overlying main roof had a smaller rotation angle, so the weighting strength of the main roof decreased and the weighting step of the main roof increased.

The working resistance monitoring results of the typical hydraulic supports in the 8305 working face are shown in Fig. 12. Among them, the #65 support was on the retained entry side, the #3 support was in the middle of the working face and the #1 support was on the uncut side of the roof. The statistical monitoring
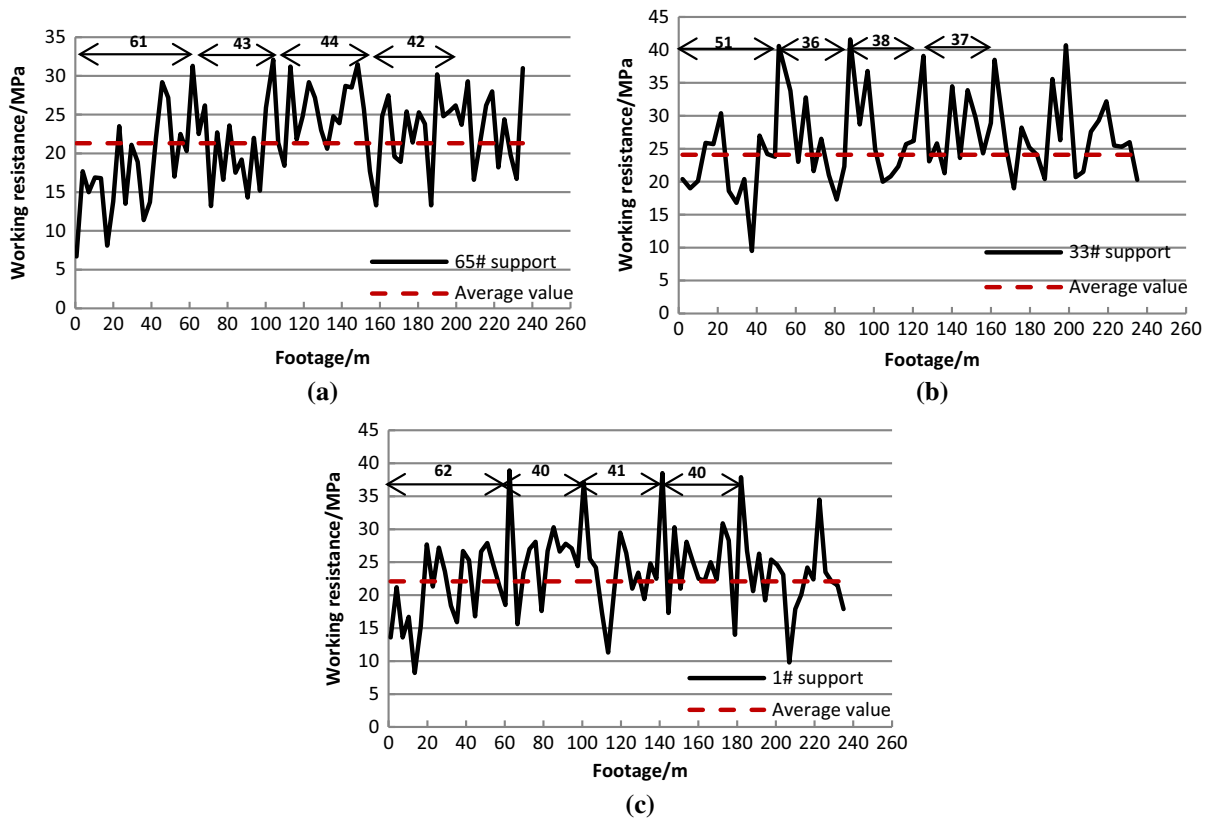
Fig. 12 Hydraulic support working resistance monitoring results (8305 working face): **a** #6 support (on the roof cutting side); **b** #3 support (in the middle of the working face); **c** #1 support (on the uncut side of the roof)

results of the typical supports are shown in Table 1. In the reuse process of the retained entry, the weighting strength in the middle of the working face was still greater than that on either side, and the mine pressure on the retained entry side still had a significant pressure releasing effect compared with that on the uncut side of the roof (the decrease in the peak strength was 6.8 MPa). Compared with the entry retaining process, the overall weighting strength of the working face was slightly weakened, and the pressure releasing effect on the retained entry side was also weakened, but the amplitude of the weighting decreases on the retained entry side, and the weighting on this side was still more uniform compared to the other side.

In the mining range of the first 100 m of the 8305 working face, according to the monitoring results of 10 marked hydraulic supports, the first weighting step, periodic weighting step, peak pressure and average pressure of the hydraulic support were counted and are shown in Fig. 13. The distribution regularity of the weighting step and weighting strength of the working face during the retained entry reuse process was consistent with the analysis results of the above typical supports. Because the anchor cables had not been

Table 1 Statistics of the working resistances of the hydraulic supports (8305 working face)

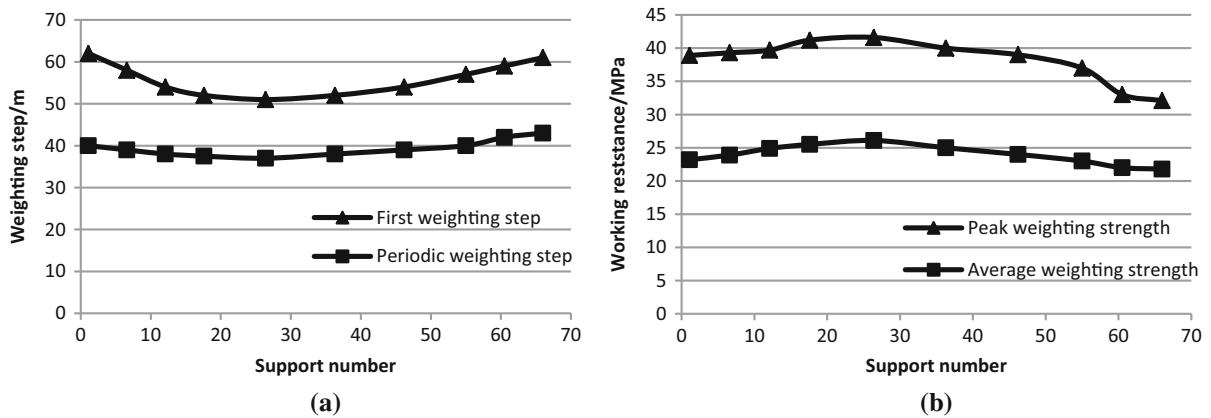| Support number	First weighting step (m)	Periodic weighting step (m)				Average pressure (MPa)	Peak pressure (MPa)
		1	2	3	Average		
1	62	39	40	41	40	22.1	38.9
33	51	36	38	38	37	24.1	41.6
65	61	43	44	42	43	21.3	32.1

Fig. 13 Featured statistics of the hydraulic support working resistances (8305 working face): **a** weighting step statistics; **b** weighting strength statistics

destroyed in the open-off cut, the first weighting basically exhibited a symmetrical distribution. While affected by the roof cutting entry retaining, the periodic weighting presented an asymmetrical distribution: after the #55 support, the periodic weighting step became longer, and the peak and average weighting strength decreased, namely, the lateral pressure releasing area on the working face was approximately 17.5 m in the retained entry reuse process.

Through the analysis of the monitoring results, it can be seen that the hydraulic supports on the retained entry side were still affected by the roof cutting entry retaining during the retained entry reuse process, but the pressure releasing magnitude and lateral influence area on the working face were smaller compared to the entry retaining process, which also confirmed the law of entry deformation in the advancing temporary support section with the retained entry reuse. Therefore, when the retaining entry is reused, the strength of the advancing temporary support should be higher than that in the entry retaining process but still lower than the lagging temporary support in the entry retaining process.

6 Conclusions

(1)   The technological process of roof cutting entry retaining and entry reuse is summarized, and the stress evolution of entry surrounding rocks is also deduced. The results can provide certain principle references for the retained entry support design during the whole life cycle.

(2)   The monitoring schemes of the entry deformation and mine pressure of working face during the entry retaining and reuse processes are proposed. The entry deformation monitoring scheme can monitor the entry dynamic deformation and determine the deformation form and main source; the mine pressure monitoring scheme can determine the lateral influence area on the working face by roof cutting.

(3)   Through practical examples involving the 8304 and 8305 working faces of the Tashan Coal Mine, it is found that the two entry sides move symmetrically between the upper and lower parts. The main deformation in the early stage of entry retaining is the displacement of the gangue wall, and the main deformation in the later stage and reuse stage is the displacement of the coal wall. The roof and floor move asymmetrically between the left and right parts, the deformation of the roof cutting side is larger at each stage, and the roof subsidence is the main source of deformation. In the follow-up application of this technology, the entry support design can be optimized according to the above laws.

Author Contributions All the authors contributed to this paper. MH conceived and designed the research. XM performed the theoretical analysis and field tests. JG provided theoretical guidance in the research process. CZ analyzed the data.

Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

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