Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 269–274

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Non-harmonious deformation controlling of gob-side entry in thin coal seam under dynamic pressure

Kegong Fan [a,*], Hongguang Liang [b], Chishuai Ma [a], Chuanwei Zang [a]

[a] State Key Laboratory of Mine Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China
[b] Liyan Mining Company of Shandong Lineng Group, Jining 273517, China

ARTICLE INFO

Article history:
Received 7 March 2014
Received in revised form
24 March 2014
Accepted 28 April 2014
Available online 14 May 2014

Keywords:
Gob-side entry under dynamic pressure
Narrow coal pillar
Non-harmonious control
Thin coal seam

ABSTRACT

The behavior of gob-side entry under dynamic pressure is totally different from the one driven after the movement of overlying strata above the adjacent coalface goaf. The gob-side entry will experience severe roof lateral structural adjustments caused by adjacent coalface mining. Thus the deformation and failure characteristics of narrow coal pillar along the gob should be carefully considered. On the basis of the data of the gob-side entry obtained in a thin coal seam under dynamic pressure, the measures to reinforce the narrow coal pillar are put forward. In addition, the non-harmonious controlling of the rock structures and non-equilibrium gob-side entry deformation is proposed to avoid potential failure. Field practices show that the supporting problems of the gob-side entry under dynamic pressure can be well addressed, which could be used in other similar mining cases.

1. Introduction

The commonly observed gob-side entry is often driven after the movement of the overlying strata above the adjacent coalface goaf, where stress redistribution tends to be stable with elapsed time. The gob-side entry is basically located in the lateral stress-reduction area, which is affected by adjacent coalface mining. Thus it can avoid potential high-stress induced damages to surrounding rocks. At present, the control technologies for surrounding rocks are pretty mature (Fan and Zhai, 2004; Bai, 2006; Liu and Meng, 2009; Hua et al., 2011). In recent years, however, replacement of mining and tunneling is difficult for the increasing mining intensity. In order to avoid forming isolated coalfaces because of skip-mining, the gob-side entry has been driven while the adjacent coalface is moving in the opposite direction at the same time (Zhang et al., 2004; Liu et al., 2010; Wang et al., 2012; Zhao et al., 2012). The stability of gob-side entry excavated during adjacent coalface mining will be affected by the strong dynamic pressure induced by mining activities. The adjustment of lateral roof structure caused by adjacent coalface mining will definitely deteriorate the stress environments and then the narrow coal pillar along the gob deforms, even fails (Golshani et al., 2007; Trifu et al., 2007). This leads to obvious non-equilibrium deformation and failure between the coal pillar and the gob-side entry, and then implement of supporting becomes more difficult (Hernández Gómez and Ruiz, 1993). Traditional supporting methods have their limits to meet the requirements of deformation control of surrounding rocks. According to the non-harmonious characteristics of rock mass structure and non-equilibrium deformation and failure in gob-side entry under dynamic pressure, the beneficial exploration is carried out in terms of the non-harmonious controlling of surrounding rocks deformation. It is of great significance for harmonizing the interaction between mining and tunneling.

2. Engineering geological settings

A case in Xuzhuang coal mine was taken to illustrate the feasibility of proposed controlling measures in this context. The primary coal seam of the first mining district is located in the second level, which belongs to the 12th coal bed of Upper Carboniferous Taiyuan Formation. The coal seam dip is 2°–8° and thickness of 1.1–1.37 m. There are 0–3 layers with the thickness of 0.20–0.33 m within the coal seam. The immediate roof is mainly made up of sandy mudstone, mudstone and in part of siltstone. The main roof is composed of sandy mudstone with the uniaxial compressive strength (UCS) of 59.0 MPa. The floor is made up of limestone with an average thickness of about 2.75 m and an average UCS of

* Corresponding author. Tel.: +86 13589290397.
E-mail address: fankeg@163.com (K. Fan).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.jrmge.2014.05.001

145.6 MPa. The interlayer floor between the coal seam and the floor (limestone) is mudstone with an average thickness of 0.2 m.

In the presence of coal seam, the main coalface is arranged in the west of the mine. Headentry of the coalface must be driven along goaf during adjacent coalface mining in order to ensure the normal operation of main coalfaces. For instance, headentry 04 lies on the east of the tail entry 02. Its cross-sectional dimension is 3.8 m × 2.6 m (width × height), which is driven along the floor by breaking the coal seam and part of roof. The narrow coal pillar (5 m wide) is left between the headentry and the adjacent tail entry. Headentry 04 has been already completed before coalface 02 mining. The combined support scheme with bolts, steel meshes and anchor cables is adopted for headentry 04. The roof bolts adopt thread steel with size of ϕ20 mm × 2000 mm and spacing of 900 mm × 900 mm. Also, steel meshes with 6.5 mm in diameter are adopted. The prestressed anchor cables of ϕ15.24 mm × 5000 mm with high strength and low relaxation are considered, and the "2-1-2" layout is used along the roadway with row spacing of 2700 mm. Fiber reinforced polymer (FRP) anchor bolts of ϕ20 mm × 1800 mm and plastic meshes are adopted at sidewalls with spacing of 700 mm × 900 mm (Fig. 1). As a typical gob-side entry under dynamic pressure, headentry 04 has experienced the dynamic pressure from mining coalfaces 02 and 04 and supporting becomes very difficult subsequently.

Considering that the original support scheme of headentry 04 cannot resist the dynamic pressure induced by adjacent coalface mining, the roadway supplementary support scheme should be used. In the supplementary support scheme, we consider high strength bolts of ϕ18 mm × 1800 mm for coal pillar side, and the nest anchor cables of ϕ15.24 mm × 5000 mm for the roof near the small pillar. Two different supporting structures are adopted for headentry 04. Anchor bolts and steel ladders are employed in Scheme I with the spacing of 900 mm × 900 mm, and in Scheme II only anchor bolts are used with spacing of 900 mm × 1800 mm. During the initial period of coalface 02 mining, Scheme II is used for the inner gob-side entry close to the cut side, where the surrounding rocks show significant plastic deformation after adjacent coalface mining. Scheme I is adopted for the outer gob-side entry in later mining. Through field investigation, the deformation and failure characteristics of surrounding rocks in the gob-side entry in thin coal seam under dynamic pressure can be well understood, providing a basis on supporting scheme selection for other gob-side entries under dynamic pressure.

The cross-section of headentry 06 is 3.8 m × 2.6 m (width × height). It will be driven along the floor by breaking the 12th coal seam and part of roof, and thus a narrow coal pillar (5 m wide) will be left. Headentry 06 is affected by coalface 04 mining when driven and by coalface 06 mining when used, and a typical roadway influenced by dynamic pressure. It can be noted that the deformation and failure characteristics of surrounding rocks in the gob-side entry under dynamic pressure should be considered in supporting scheme.

3. Deformation and failure characteristics of surrounding rocks in gob-side entry in thin coal seam under dynamic pressure

The gob-side entry under dynamic pressure roughly experiences three stages, i.e. roadway excavation, adjacent coalface mining, and mining of target coalface. Based on field monitoring of ground pressure in the reinforced area of headentry 04 where Scheme II was employed, the deformation and failure characteristics of surrounding rocks in the gob-side entry under dynamic pressure are listed as follows:

(1) The front abutment pressure caused by adjacent coalface mining has a minor influence on the gob-side entry under dynamic pressure. In a certain area in vicinity of roadway affected by the front abutment pressure, the maximum convergence between the roof and floor is up to approximately 21 mm, and that of

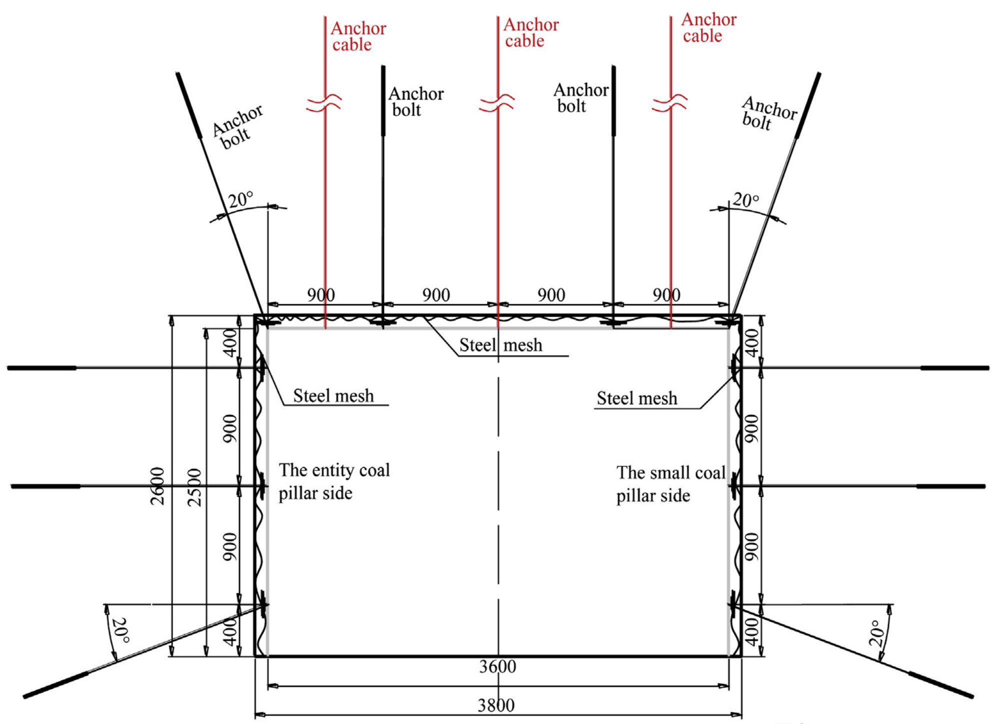


Fig. 1. Support profile of headentry 04.

sidewalls is about 118 mm, suggesting the effectiveness of the adopted support scheme (in Fig. 2).

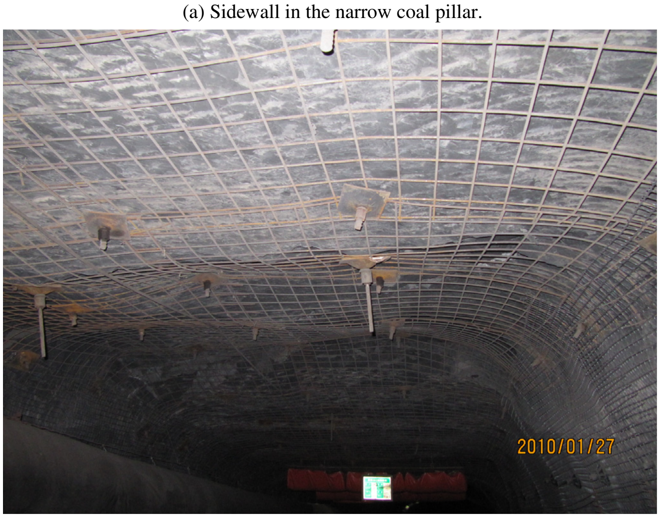
(2) The surrounding rocks in the gob-side entry under dynamic pressure show significant plastic deformation after mining adjacent coalface. In this circumstance, slip surfaces between narrow coal pillar and roof strata are easy to occur. Sidewalls slippage in some areas with a value of 500–800 mm. In Fig. 3, we can observe the coal–rock interface characterized by obvious slipping traces. However, the lateral deformation of the solid coal is smaller (basically less than 150 mm) and sidewall slippage is reported in very few areas, showing evident non-equilibrium deformation and failure of surrounding rocks.

(3) The dynamic pressure caused by adjacent coalface mining has a long-term effect on mining stability. The strong deformation of surrounding rocks in gob-side entry under the dynamic pressure (the sidewalls convergence speed of more than 10 mm/d is deemed as strong active stage) lasts for about one month within scope of 90 m after the coalface mining, which is within 90 m around dynamic pressure. The general deformation (the sidewalls convergence speed of less than 2–10 mm/d is considered as active stage) lasts for about three months within scope of 250–270 m after coalface mining.

(4) Many phenomena of serious deformation and/or failure occurred in the coal pillar: (i) FRP anchor bolts were pulled out and anchor plates were broken. (ii) The double anti-pulling mesh was cut by the high strength anchor plates. The anchor bolts and anchor plates sometimes penetrated into the reinforced body. In contrast, the FRP anchor plates were crushed or fell off only in local areas for the solid coal sidewall.

(5) The roof convergence of the gob-side entry was smaller under dynamic pressure. In this regard, mesh bag and mesh breakage were observed in some local broken roof.

(a) Sidewall in the narrow coal pillar.



(b) Roadway roof.

Fig. 2. Situations of headentry 04 affected by the front abutment pressure.

(a) Overall outward movement of sidewall in the narrow coal pillar.

(b) Slip phenomenon of sidewall in the narrow coal pillar.

Fig. 3. Horizontal movement of narrow coal pillar in headentry 04 and its effects.

The deformation and failure characteristics of the gob-side entry under dynamic pressure show that the FRP bolts cannot provide large pre-load and/or clamping force and thus enough anchoring force, suggesting their poor capacity against dynamic pressure. Some accidents verified the tensile failure of FRP bolts, crushing failure and slippage of FRP anchor plates. In the later period, we adopted Scheme I to reinforce the outer headentry 04 in order to effectively control the deformation of the coal pillar.

4. Stability analysis of the gob-side entry under dynamic pressure

The above-mentioned analysis indicates that the deformation and failure of gob-side entry under dynamic pressure are induced

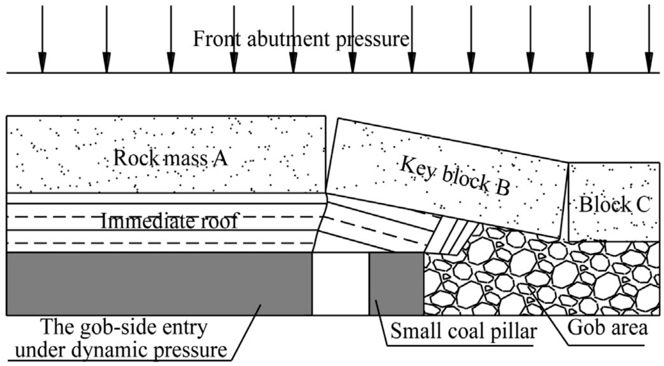


Fig. 4. Arc-triangle block of gob-side entry under dynamic pressure (Zhu, 1987; Hou and Li, 2001; Zhang et al., 2004; Bai, 2006).

mainly by mining adjacent coalface. In the initial period of roadway excavation, one side of the gob-side entry is the solid coal and the other side is the narrow coal pillar and untapped solid coal. The narrow coal pillar is basically believed to be almost intact and its bearing capacity is not reduced when the gob-side entry is located at the front of adjacent coalface. The front abutment pressure caused by adjacent coalface mining has a great influence on the gob-side entry at the front of coalface, and strata behaviors are comparatively weaker. With the adjacent coalface advancing, the arc-triangle block structure is formed after periodic weighting of the main roof behind adjacent working face (Zhu, 1987; Hou and Li, 2001; Zhang et al., 2004; Bai, 2006). Arc-triangle block B, adjacent caving block C, and rock A above the coalface without caving are articulated together, as shown in Fig. 4. The formation of arc-triangle block is a dynamic process affected by strong dynamic pressure caused by the rotation and subsidence of the structure, the roof of the gob-side entry below the key block B will experience adaptive subsidence under dynamic pressure, along with overall inward movement of sidewalls. After this structural adjustment, the surrounding rocks of gob-side entry deform seriously and become unstable.

The behavior of gob-side entry under dynamic pressure is totally different from the one driven after the movement of overlying strata above the adjacent coalface goaf. The gob-side entry will experience severe roof lateral structural adjustments caused by adjacent coalface mining. Under the lateral abutment pressure caused by adjacent coalface mining, the narrow coal pillar in vicinity of adjacent coalface is damaged firstly due to intense stress concentration, fractures, and rotating subsidence of arc-triangle block. The stress distribution, bearing capacity and deformation of the coal pillar are also significantly different from those of solid coal in gob-side entry under dynamic pressure. Affected by the deformation and failure of narrow coal pillar, other parts of roadway surrounding rocks may cause roadway instability for the action of stress redistribution. It can be seen that the lateral fracturing and rotating subsidence of main roof of the adjacent coalface are the major reasons for the large deformation of surrounding rocks in the gob-side entry under dynamic pressure. The narrow coal pillar plays an important role in controlling roadway deformation and maintaining roadway stability, and its deformation and failure will directly affect the roadway stability. Therefore, the narrow coal pillar is the key, also a difficulty, for supporting.

5. Support scheme and analysis

5.1. Support method

The site-specific conditions of headentry 06 are described as follows:

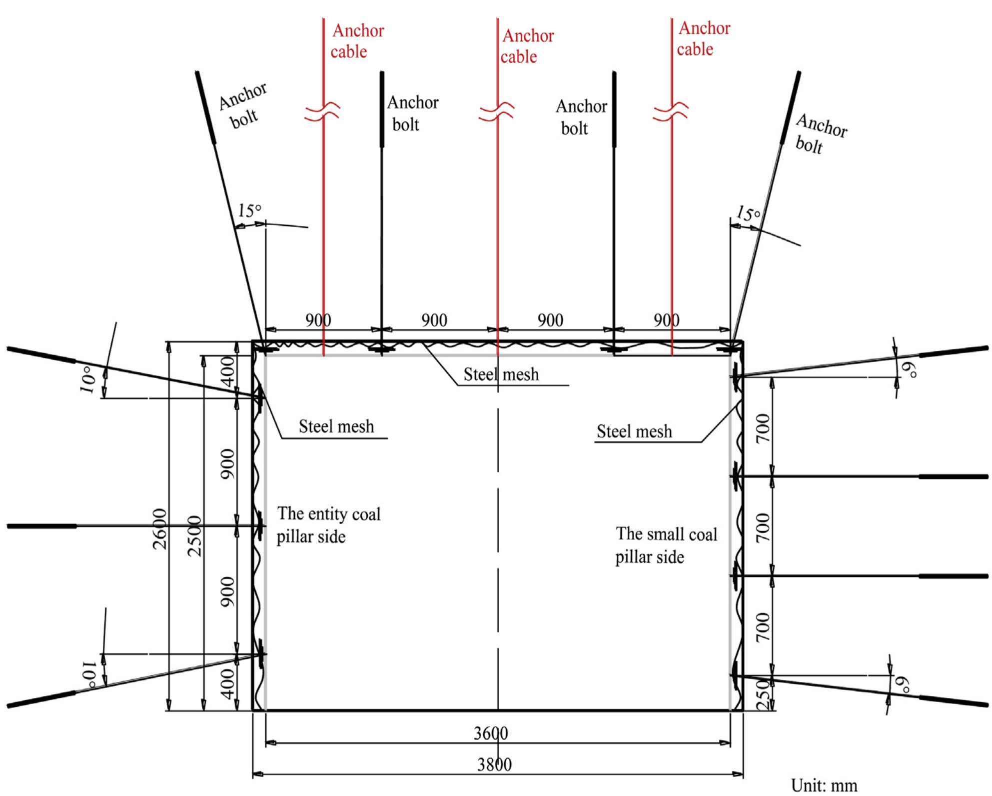


Fig. 5. Support cross-sectional drawing of headentry 06.

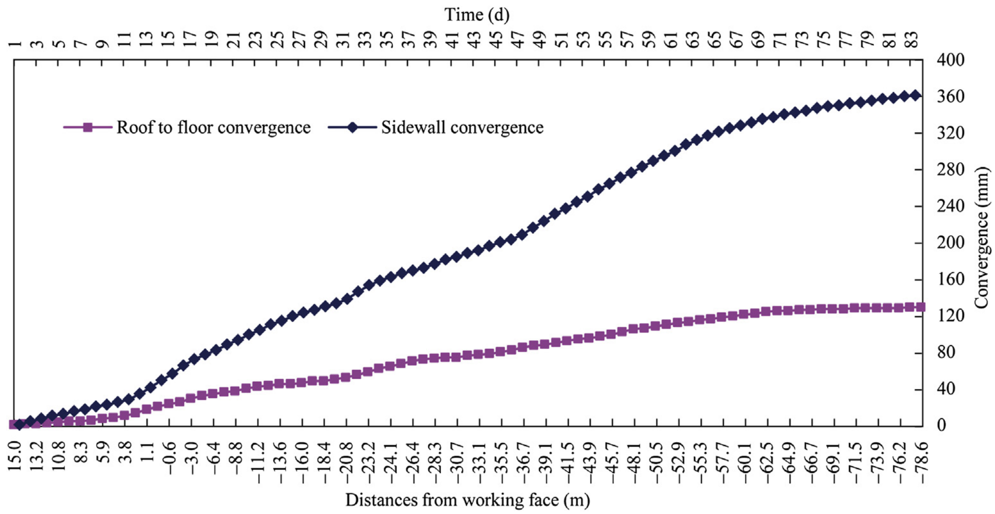


Fig. 6. Typical surface displacement of gob-side entry under dynamic pressure induced by adjacent coalface mining.

(1) Headentry 06 is driven along the floor by breaking the coal seam and part of main roof, and the thickness of coal seam is about half of the roadway height.
(2) A narrow coal pillar (5 m wide) is left for gob-side entry driven along tail entry 04.
(3) The roadway is influenced by coalface 04 mining.
(4) Unbalanced stress in rock mass, bearing capacity variation and non-equilibrium deformation and/or failure of gob-side entry under dynamic pressure are existing.

According to the above-mentioned descriptions, the combined support scheme with high strength prestressed anchor bolt, prestressed anchor cable and steel mesh is adopted, which is based on the non-harmonious control concept, support principles, and the bearing capacity of surrounding rocks. The narrow coal pillar is reinforced in order to control the deformation of gob-side entry under dynamic pressures. Field monitoring results show that the deformation of roadway matches well with that of asymmetric supporting structure.

5.2. Support scheme

Headentry 06 has the cross-sectional dimension of 3.8 m × 2.6 m (width × length). Anchor bolts are arranged at the narrow coal pillar and the solid coal, asymmetrically, as shown in Fig. 5. Support parameters are listed as follows:

(1) The high strength bolts of ϕ20 mm × 2000 mm are adopted for the roof, with spacing of 900 mm × 900 mm. The cold hard drawn steel wire for welded mesh is adopted with diameter of 4.5 mm, and grid size of 100 mm × 100 mm, and dimension of 2000 mm × 1000 mm. The prestressed anchor cables with high strength and low relaxation are employed with dimension of ϕ15.24 mm × 5000 mm. The layout of "2-1-2" pattern with row spacing of 1800 mm along the roadway is utilized to improve supporting effect.
(2) Non-harmonious bolting with metal mesh is adopted at sidewalls. Bolts of ϕ20 mm × 2000 mm are adopted at the coal pillar with spacing of 700 mm × 900 mm. FRP bolts of ϕ20 mm × 1800 mm are adopted at the solid coal side with spacing of 900 mm × 900 mm. The metal meshes, 4.5 mm in diameter, dimension of 2500 mm × 1000 mm and grid size of 100 mm × 100 mm, are adopted at sidewalls.

5.3. Result analysis

Field observation shows that the surface displacement is small under dynamic pressure induced by adjacent coalface mining. After excavation, the maximum cumulative horizontal displacement of sidewalls is 280–370 mm, significantly reduced when compared to that of headentry 02. Cumulative convergence between roof and floor is 76–130 mm. It is noted that the overall outward movement of sidewalls makes the horizontal deformation become larger, while the convergence between roof and floor is relatively smaller. Observation shows that the convergence of coal pillar accounts for about 70% of the sidewall movement. The surface displacement of roadway tends to be stable after excavation of 70–90 m from monitoring station. The typical surface displacement of roadway is shown in Fig. 6.

6. Conclusions

(1) Under dynamic pressure, the bearing capacities of the coal pillar and the solid coal are totally different, especially when the gob-side entry is in vicinity of the adjacent coalface. Accordingly, the asymmetric characteristics of surrounding rocks should be considered.
(2) Affected by adjacent coalface mining, slipping surfaces between narrow coal pillar and roof strata can be formed, leading to the overall outward movement and larger deformation, even if the overall outward movement of solid coal is smaller. Non-equilibrium deformation and failure of the gob-side entry appear.
(3) Support measures play an important role in controlling the stability of gob-side entry under dynamic pressure. According to the non-equilibrium deformation and failure of surrounding rocks, it is advised to adopt non-harmonious supports to reinforce the narrow coal pillar. Hence the deformation of the surrounding rocks of gob-side entry under dynamic pressure can be effectively controlled.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This paper is supported by the National Natural Science Foundation of China (Grant No. 51104093).

References

Bai JB. Surrounding rock control of gob-side entry driving. Xuzhou: China University of Mining and Technology Press; 2006 (in Chinese).

Fan KG, Zhai DY. Analysis of deformation failure and non-harmonious control mechanism of surrounding rocks of roadways with weak structures. Beijing: China Coal Industry Publishing House; 2004 (in Chinese).

Golshani A, Oda M, Okui Y, Takemura T, Munkhtogoo E. Numerical simulation of the excavation damaged zone around an opening in brittle rock. International Journal of Rock Mechanics and Mining Sciences 2007;66(4):835–45.

Hernández Gómez LH, Ruiz C. Experimental evaluation of crack propagation velocity in PMMA under dynamic pressure loading. International Journal of Fracture 1993;61(2):R21–8.

Hou CJ, Li XH. Stability principle of big and small structures of rock surrounding roadway driven along goaf in fully mechanized top coal caving face. Journal of China Coal Society 2001;26(1):1–7 (in Chinese).

Hua XZ, Liu S, Liu ZH, Zha WH, Li YF. Research on strata pressure characteristic of gob-side entry driving in island mining face and its engineering application. Chinese Journal of Rock Mechanics and Engineering 2011;30(8):1646–51 (in Chinese).

Liu JH, Zhao ZH, Mou GL. Research on support technology for roadway under strong dynamic pressure while mining in fully mechanized caving face and its application. Mining and Metallurgical Engineering 2010;30(2):14–7 (in Chinese).

Liu QT, Meng FW. Support technology of narrow coal pillar goaf-side gateway for fully mechanized top coal caving mining face in deep mine. Coal Science and Technology 2009;37(7):28–30 (in Chinese).

Trifu CI, Shumlia V, Chen D. Investigation of rock mass stability through the analysis of failure components of microseismicity at Darlot gold mine, Austria. In: Challenges in Deep and High Stress Mining. Perth, Australia: Australian Centre for Geomechanics; 2007.

Wang M, Bai JB, Wang XY, Xu Y, Guo YH, Cao JL. The surrounding rock deformation rule and control technique of the roadway driven along goaf and heading for adjacent advancing coal face. Journal of Mining and Safety Engineering 2012;29(2):194–202 (in Chinese).

Zhang N, Li XH, Gao MS. Pretensioned support of roadway driven along next gob and heading adjacent advancing coal face and its application. Chinese Journal of Rock Mechanics and Engineering 2004;23(12):2100–5 (in Chinese).

Zhao Y, Wang J, Gao MS, Liu BT. Research and application of gateway driving along goaf forward to adjacent mining coal mining face in Chensilou mine. Coal Engineering 2012;6:41–3 (in Chinese).

Zhu DR. Fracture character of main roof in longwall face and its application. PhD Thesis. Xuzhou: China University of Mining and Technology; 1987 (in Chinese).

Dr. Kegong Fan, is a professor in Shandong University of Science and Technology, and his main research interest covers ground pressure and strata control, roadway support. To date, as a principal investigator, Dr. Fan has participated in over 60 projects. He was awarded the Second State-level Prize of “Achievements in Education”, and provincial- and ministerial-level Science and Technology Progress Awards. Dr. Fan is the author of *The Failure and Instability Analysis and Non-harmonious Control Mechanism of Weak Structure of Surrounding Rocks in Roadways*, and the co-author of 6 books. He has published more than 50 academic papers. At present, he is the committee member of China Coal Society for Coal Mining Specialized Committee.