Int J Coal Sci Technol (2017) 4(4):301–309
https://doi.org/10.1007/s40789-017-0188-8

Surrounding rock control theory and longwall mining technology innovation

Guofa Wang[1] · **Yihui Pang**[1]

Received: 1 November 2017 / Revised: 23 November 2017 / Accepted: 25 November 2017 / Published online: 4 December 2017

Abstract To accommodate surrounding rock structure stability control problem in underground mining, we study the coupling effect principle between hydraulic support and surrounding rock, and develop a series of longwall mining technology and equipment, which solves four common technical problems that significantly undermine coal mining safety, efficiency, and high recovery and extraction rates. Based on the coupling characteristic between mining-induced stress field and supporting stress field of hydraulic support, we identify six controllable factors in the application of hydraulic support to surrounding rock, and further reveal the relationship between hydraulic support and surrounding rock in terms of the strength, the stiffness, and the stability coupling. Our findings provide a plausible solution to the longwall mining technical problem with 6–8 m mining height. By analyzing the dynamic disequilibrium characteristics between hydraulic support and surrounding rock, we propose the intelligent top coal caving control method and the high-coal-recovery-rate technology for fully mechanized caving faces. With the invention of this technology, China is likely to lead the world in terms of the fully mechanized top coal caving mining technology. We are also the first to employ the intelligent coupling technology between hydraulic support and surrounding rock, and automated mining mode, and supporting system cooperative control with automatic organization. We develop the comprehensive multi-index intelligence adjusting height decision-making mechanism and three-dimensional navigation automatic adjusting straightness technology based on shearer cutting height memory association, cutting power parameters, vibration, and video information, leading to the first set of intelligent longwall mining technology and equipment for thin seam. Our innovation makes a solid contribution to the revolution of intelligence mining technology. With the innovative use of three-dimensional coupling control principle for surrounding rock, we successfully resolve the technological difficulties of longwall mining equipment and surrounding rock control for steep dipping seam, making a breakthrough of longwall mining technology with steep dipping seam.

Keywords Surrounding rock control · Hydraulic support · Thick coal seam · Thin coal seam · Steep dipping seam

1 Introduction

There have been four major stages of coal mining development in China, namely artificial mining, blasting mining, conventional mechanized mining, and fully mechanized mining. The mining practice suggests that the fully mechanized mining method was the basic solution for guaranteeing safety, efficiency, and high recovery ratio mining of underground coal mining. The development of longwall mining equipment technology epitomizes the mining method change. In this revolution, hydraulic support is the core equipment for surrounding control. The

Supported by the National Key Research and Development Program of China (2017YFC0603005).

✉ Yihui Pang
pangyihui@tdkcsj.com

[1] Coal Mining and Design Branch, China Coal Research Institute, Beijing 100013, China

improvement of hydraulic support model has become a milestone of longwall mining technology development and a decisive factor of mining technology innovation. The adaptation and reliability of hydraulic support and matching system determine the success of the longwall mining technology (Gong and Jin 2008; Wang 2010).

In the past 30 years, China's coal production has increased from 872 million tons in 1985 to 3685 million tons in 2015, and the death rate per million tons has dropped form 7.63 in 1985 to 0.157 in 2015, suggesting that the coal mining efficiency has increased more than 30 times, and the death rate per million has declined nearly 50 times, and the roof accident deaths has decreased by 99.4%. For some coal mines, the death rate per million tons is almost zero, which achieves safety, efficiency, and high-recovery-rate mining (Wang et al. 2006; Xu et al. 2015; Wang and Pang 2016). These achievements mainly benefit from China's development and progress in longwall mining technology and equipment.

At present, the key technical problems to achieve coal mining safety, efficiency, and high recovery ratio are the surrounding rock control in strong strata behaviors working face and the safety, efficiency mining technology, and equipment development in complicated mining seam. To accommodate the above-mentioned mining problems, this paper studies "hydraulic support and surrounding rock coupling control theory and technology" based on long-term technological research and innovation practice. The sets of longwall mining technology and equipment had developed for thick coal seams longwall mining with high cutting, super high seam full-mechanized caving mining with high cutting, thin coal seam automated and intelligent mining, and complicated steep dipping seam, which could solve four typical coal seams working faces mining problems with safety supporting, automated mining, high production, high efficiency, and high recovery ratio.

2 Hydraulic support and surrounding rock coupling principle

The surrounding rock coal mining brakes the equilibrium state of in situ stress filed. The surrounding rock experience deformation, destruction, caving and stability under the coupled action of mining stress field and supporting stress field (Gao and He 2010; Ju et al. 2012). Based on the independently researched and developed longwall mining working face supporting quality monitoring system, we identify the six controllable parameters of hydraulic support to surrounding rock through many field observations of hydraulic support and surrounding rock. These factors include the hydraulic support setting load and working resistance, the top beam action point of resultant force, the horizontal applied force from the top beam to roof rock, the face guarding moment, the distance from beam to rib, and working face mining rate. We optimize the six parameters to control the surrounding rock stability.

We improve the surrounding rock self-bearing capacity by studying the "multi-field coupling" between hydraulic support and surrounding rock. The essential of working face supporting is the coupling relationship in the strength, the stiffness, and the stability between hydraulic support and surrounding rock, as shown in Fig. 1.

In the dynamic equilibrium system of hydraulic support and surrounding rock, the surrounding rock deformation and instability induced by the mining stress field jointly determine the system stability. The hydraulic support could adapt and influence the process of surrounding rock motion by actively adjusting stress state to protect the safety working space in working face. In other words, the hydraulic support's supporting intensity should adapt the surrounding rock's strength to reduce the impact of dynamic load from the surrounding rock by actively protecting and reasonably yielding. The hydraulic support's supporting stiffness should adapt the surrounding rock's stiffness to change the dynamic load location of roof by optimizing the structural stiffness of hydraulic support, providing safe working space. The support system's stability should adapt the surrounding rock's stability to control the dynamic instability of surrounding rock based on the stability of hydraulic support itself.

Based on the coupling principle of hydraulic support and surrounding rock, we invent the hydraulic support three-dimensional design method and software system (Wang et al. 2011; Wang and Pang 2015), as shown in Fig. 2. The motion skeleton of hydraulic support is established by PROE 3D design software, and goes through dynamics analysis of hydraulic support state of motion to finalize the reasonable technical parameters of hydraulic support. We also analyze the assembly unit and whole hydraulic support using ANSYS to guarantee the strength design, the stiffness, and the stability of hydraulic support.

Based on the coupling relationship between hydraulic support and surrounding rock, we establish the adaptability evaluation model of hydraulic support and surrounding rock, which allows comprehensive evaluation of the adaptability of hydraulic support. We divide the hydraulic support and surrounding rock system into strength coupling subsystem, stiffness coupling subsystem, and stability coupling subsystem, and then build the evaluation index system based on the adaptive composite index of hydraulic support and surrounding rock, as shown in Fig. 3.

To meet the differential needs of the surrounding rock controlling effect of hydraulic support for different coal seams, we calculate the preference coefficient matrix of the different evaluation indicators. We use the weight as the

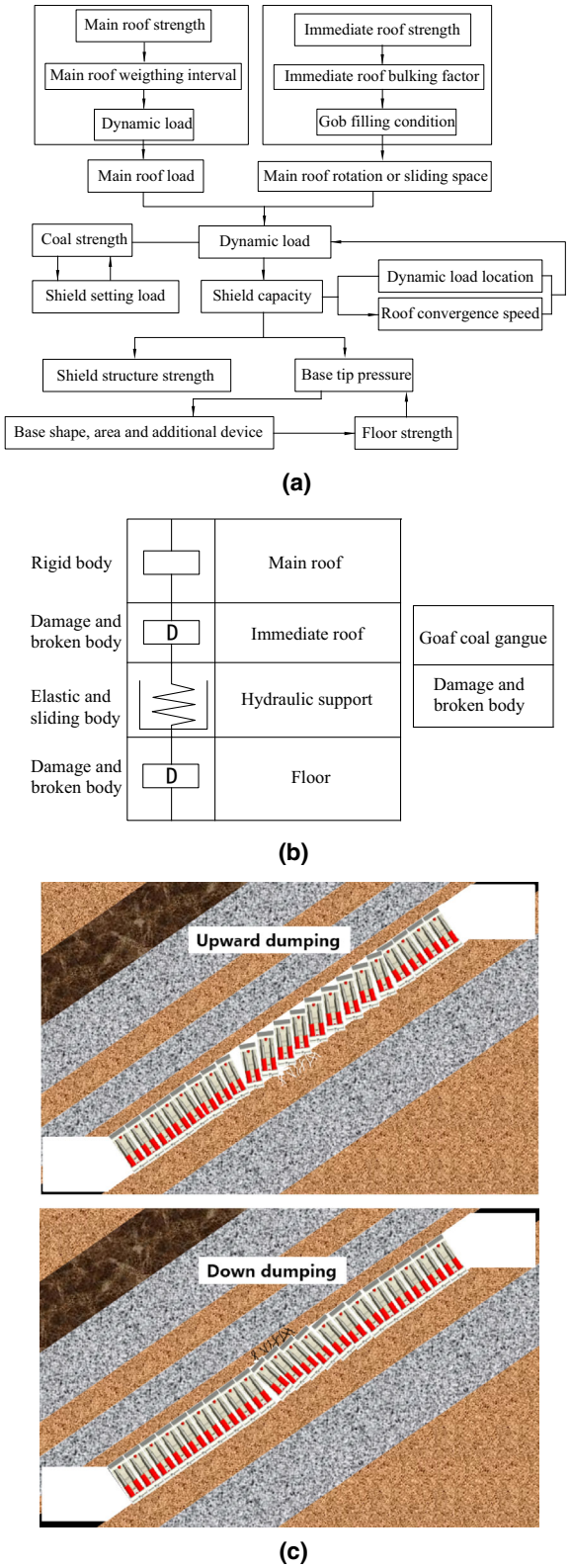


Fig. 1 Coupling relationship between hydraulic support and surrounding rock. **a** Strength coupling relationship, **b** Stiffness coupling relationship, **c** Stability coupling relationship

value of superiority degree corresponding to the evaluation index, and adopt the FCE method to build the adaptive evaluation matrix of hydraulic support and surrounding rock. The adaptive evaluation results of hydraulic support could guide the design to improve hydraulic support.

3 Key technology and equipment of longwall mining with super high cutting

The thick coal seam reserves account for 45% of total coal reserves, and many 6–8 m thick coal seams exist in the large-scale mining areas in Western China. The slicing method for this type of coal seam has problems of low efficiency, low profits, and great security rick, etc. (Sasaoka et al. 2016). The fully mechanized mining method with high or super high cutting suits this type of coal seam well, but increasing cutting height could lead to stronger mining pressure behavior and substantially raise the rib and roof control risk. Therefore, it is imperative to solve the problem of the multi-field coupling relationship of hydraulic support and surrounding rock as well as the system adaptability and reliability assurance technology for longwall mining with super high cutting.

Based on the coupling relationship between hydraulic support and surrounding rock, we propose the double factors control method to confirm the reasonable working resistance of hydraulic support. The first factor, the working resistance of hydraulic support should control the roof subsidence effectively by using the roof self-bearing capacity. The second factor, the working resistance and rib guard force of hydraulic support should prevent rib spalling and reduce the rib failure depth. The reasonable working resistance of hydraulic support should meet above two conditions at the same time.

Based on the surrounding rock deformation and instability feature of longwall mining working face with super cutting height, we establish the roof strata "cantilever + voussoir beam" structural mechanics model and rib "tension-slippage" coupling mechanical model (Pang and Wang 2017a, b), as shown in Fig. 4.

We develop the impact resistance column with diameter of 530 mm based on energy dissipation theory, the micro-clearance and quasi-rigid four bar mechanism, the three-level coordinating action rib guard appliance, and the large flow and high pressure intelligent supply system to solve the surrounding rock stability control problems caused by the massive space, the super strong mine ground pressure, super high rib, and strong disturb stratum movement in longwall mining working face with super cutting height. The life span of hydraulic support has increased from 5000 working cycles to 60000.

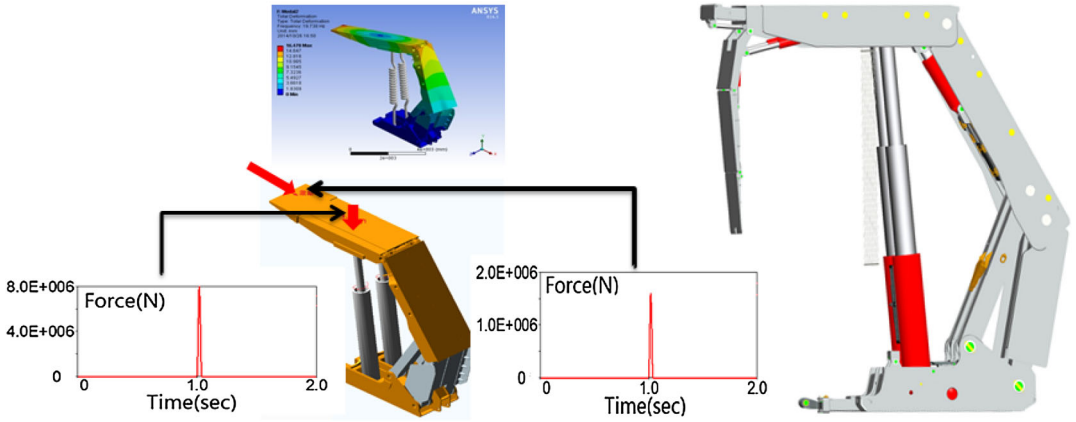


Fig. 2 Hydraulic support three-dimensional dynamic optimization design

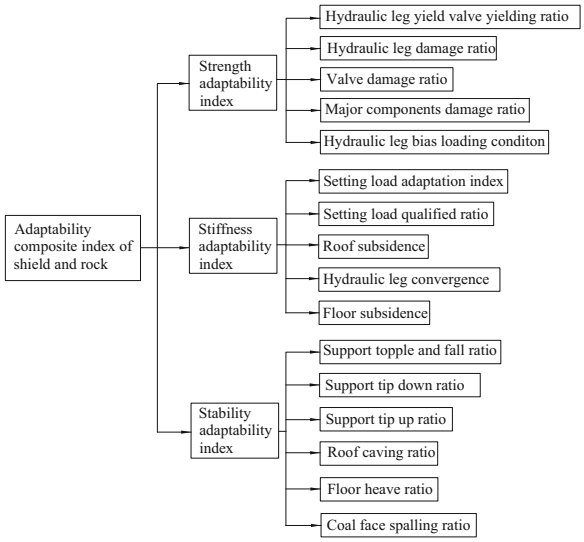


Fig. 3 Hydraulic support and surrounding rock adaptability evaluation indexes

Due to a height difference of 2–4 m between the working face and the roadway (the working face cutting height was 7–8 m, and the roadway height was 4–4.5 m) in longwall mining working face with super height cutting, the traditional step-by-step matching manner leads to substantial triangle coal loss. To solve this problem, we introduce the large gradient transition matching manner for 7 m cutting height or the large gradient + short gradual transition for 8 m cutting height and supporting equipment to achieve one-time transition from working face to roadway, which could recycle more than 0.4 million tons coal in one working face, as shown in Fig. 5.

The whole set of technology and equipment that we develop could exploit coal 6 million tons per year, which is the first time that imported products are completely replaced with the domestic high-end longwall mining technology and equipment. The first set of longwall mining technology and equipment for 7.2 m cutting height were successfully launched and were used at Hongliulin mines in 2011. The working face production reached 12 million tons per year. In 2014, to accommodate the 6–8 m hard and thick coal seam of Jinjitan coal mines, the hydraulic support (ZY21000/38/82D) and the set of longwall mining technology with the biggest cutting height and the greatest working resistance in the world were launched. The three-level coordinating action rib guard appliance for super height hydraulic support and the impact resistance column with diameter of 530 mm based on energy dissipation theory were introduced with a breakthrough of the hydraulic support structural, material and manufacturing technique, which solved the problem of stability and reliability due to the large-scale and high-dynamic-pressure sensitive structure of hydraulic support.

4 Fully mechanized caving mining technology and equipment with large mining height for super thick coal seam

The fully mechanized caving mining, marked by the employment of the top coal caving hydraulic support, tested and developed in the early 1980s went through three important stage of development: high-level caving, middle-level caving, and low-level caving. It has been widely shown that the top coal caving hydraulic support is the decisive factor that makes the fully mechanized caving mining the safe, efficient, and high-recovery mining technology for thick and super thick coal seam.

Through a number of observations and high-volume in-depth analyses for top coal deformation rule and mining pressure revealing rule, we find the dynamic unbalanced coupling characteristics between hydraulic support and top coal in fully mechanized caving face. The load of hydraulic support is time-varying load, which changes along with the

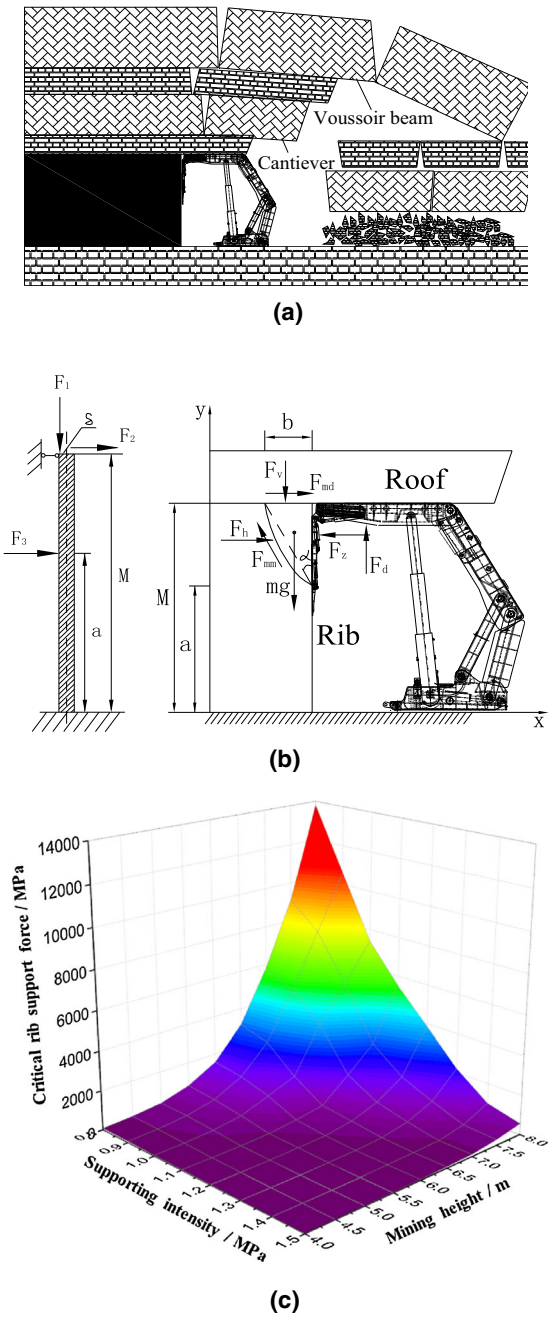


Fig. 4 Coupling mechanical model between hydraulic support and surrounding rock. **a** "Cantilever + voussoir beam" structural mechanics model, **b** "Tension-slippage" mechanical model, **c** relationship of supporting intensity and critical rib support force in different mining height

top coal caving (Chen et al. 2007; Wang et al. 2012; Liu et al. 2015). To solve the safety, efficiency and high-recovery-rate mining problem, we develop the fully mechanized caving mining technology and equipment with large mining height for super thick coal seam. We build the "combined cantilever" mechanical model for top coal and roof stratum, and further identify and solve the contradiction between rib spalling and top coal caving and drawing characteristics. This is the first study to quantitatively analyze the top coal failure depth and lumpiness from the hydraulic support to top coal, as shown in Fig. 6. This study solves the problems of super mining space overlying strata moving law, super high rib stability control, super thick top coal caving law due to 15–20 m super coal seam mining, and also improves top coal recovery ratio technology in Datongtashan coal mine, which is the world's first set of fully mechanized caving mining technology and equipment with large mining height for super thick coal seam, increasing the top coal caving efficiency by 40% and setting a world record of 1.3 million tons per month with no accidents.

To accommodate the hard and heavy coal seam condition in the mines of Western China, we introduce the intelligent top coal caving control method and set of technology. Based on the coupling relationship between hydraulic support and surrounding rock, we develop the intelligent coupling control system of hydraulic support and surrounding rock, which allows real-time monitoring for the posture and stress state of hydraulic support. Based on the hydraulic support intelligent coupling control appliance and top coal caving automatized control appliance, we study the sequential control automatized caving logical relationship based on the section multi-window multi-wheel coal technology, and propose the top coal caving time control method based on the fruit fly optimization algorithm and RBF mixed-forecast, which could adjust caving time automatically and record the manual intervention condition at the same time. The top coal caving experiment results show that the average response time of the top coal caving mechanism is 1.43 s.

To increase the top coal caving ratio of hard and heavy coal seam, we invent the strong disturb three-level high efficiency caving device to fit with the hard-top coal condition, as shown in Fig. 7. Compared to the conventional caving device, the caving space in the back of the hydraulic support increases by 23%, significantly decreasing the arching probability and improving the top coal recovery ratio.

To solve the problem that the transition hydraulic support cannot cave top coal when the rear scraper conveyer, which occupies the back-caving space with the drive unite, adopts the matching manner of end capacity discharge, we design the cross side-discharge scraper matching manner, as shown in Fig. 8, which raises the top coal recovery ratio by more than 1.5%. This design solves the problem of automatic control for transition hydraulic support of supporting system and increases the non-failure operation time by more than 10%.

The fully mechanized top coal caving automated mining has been used for super thick coal seam in Aosida coal

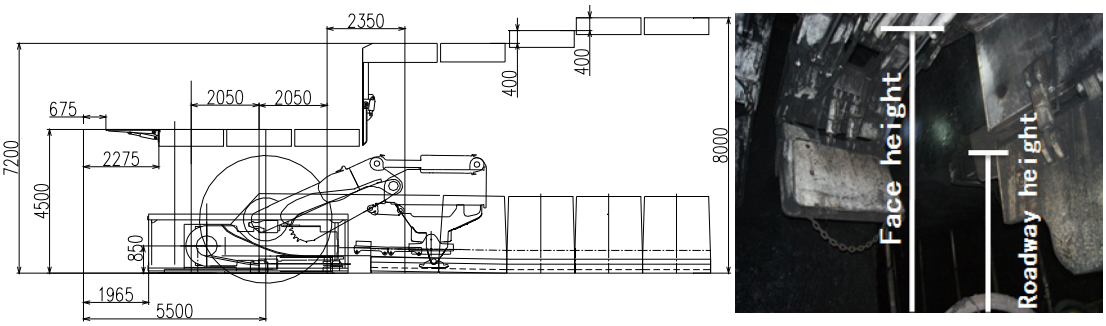


Fig. 5 Equipment matching manner for super cutting height working face

mine of Australia, which improved the recovery ratio by 12%, improved the labor efficiency by 41%, decreased the number of workers by 72%, and has been extended to regions such as Shandong, Shanxi, Inner Mognolia, etc.

5 Intelligent fully mechanized mining technology and equipment for thin coal seam

More than 85% of the mines in China have thin coal seam < 1.3 m, which is mainly mined as protective layer for the lower coal seam. Due to the unsteady thickness of the thin coal seam, the mining space is narrow and small. There has been a contradiction between the capacity and the size of equipment. The imported advanced fully mechanized coal mining equipment can only be applied to the coal seam more than 1.5 m and cannot be used for safety and high-efficiency mining for the coal seam < 1.3 m and has become the technology bottleneck for the coal sustainable development (Wang 2013, 2014; Pang et al. 2015).

To solve the problem of safety and high-efficiency supporting for thin coal seam with unsteady thickness, we introduce intelligent coupling technology between hydraulic support and surrounding rock, automatic mining patter and supporting system cooperative control with automatic organization (Hargrave et al. 2017). We develop the comprehensive multi-index intelligence adjusting height decision-making mechanism and three-dimensional navigation automatic adjusting straightness technology based on shearer cutting height memory association, cutting power parameters, vibration and video information, which solve the problem of the hydraulic support followed the coal cutter moving by automatic control and the coal cutter cleaning the float coal after beveling cutting the tringle coal automatically. We also invent the super large-scale magnification ratio hydraulic support, which adopts the new structure design of panel top beam, the double linkage and double equilibrium jack fold the position, and the double-telescopic prop with single liquid into the mouth to break through the minimum mining height limit. The super large-scale magnification ratio hydraulic support, which fits in with the 0.5–1.4 m coal seam, is built to tackle the technical challenges of small size equipment, superpower, and automatic control.

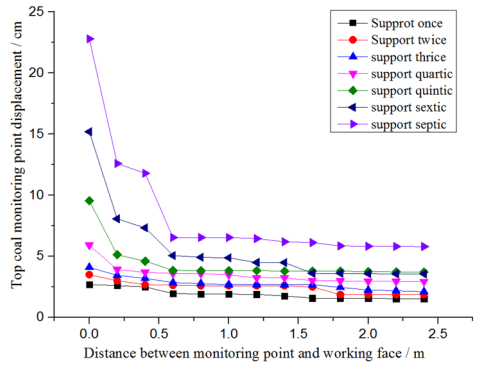
The automatic mining equipment and technology, which is developed for thin coal seam, solves the problem of coal seam unstable thickness, thick and hard dirt band, complicated condition for 0.6–1.3 m thin coal seam in Jizhongnengyuan, and realizes automatic mining with supervisor and automatic operation.

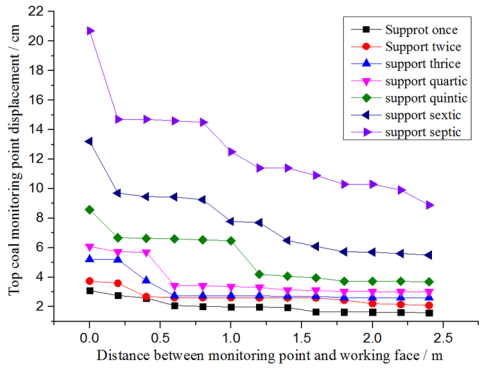
To accommodate the thin coal seam (1.7–2.5 m) intelligent mining problem in Huangling No.1 coalmine, as shown in Fig. 9, we address the following problems: automatic continuous mining in complicated coal seam, automatic supporting in the working face end and forward section, intelligent perception and steady transmission, mining height intelligent decision control and system reliability, etc. We carry out the top-level design of intelligent mining system and system integration matching to accomplish the remote monitoring normalization and the intelligent mining with unmanned operation in working face.

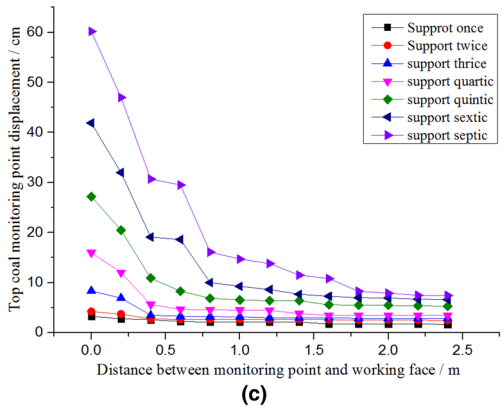
Authorized by the State Administration of Work Safety, the Innovation Center for Intelligent Mining of Coal Mines has been established, focusing on intelligent mining key innovation, promotion and technical standards system research, such as intelligent working face system integration matching design standard research, intelligent working face safety evaluation and security technology standard, intelligent working face quality management technique standard, intelligent working face remote control operation technique standard, intelligent working face manual work technique standard, intelligent working face equipment health management standard, etc.

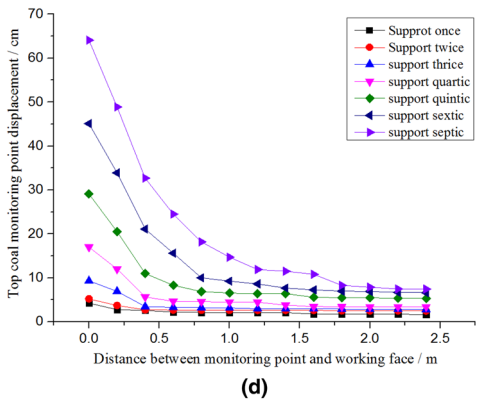
6 Longwall mining technology and equipment for steep dipping seam

The steep dipping seam refers to the coal seam with the dip angle of 35°–55°. Since the dip angle of coal seam is relatively large, the working face is vulnerable to the instability









◀**Fig. 6** Top-coal time-displacement curve due to hydraulic support supporting again and again to top-coal. **a** Supporting stress 0.3 MPa, **b** Supporting stress 0.6 MPa, **c** Supporting stress 0.9 MPa, **d** supporting stress 1.2 MPa

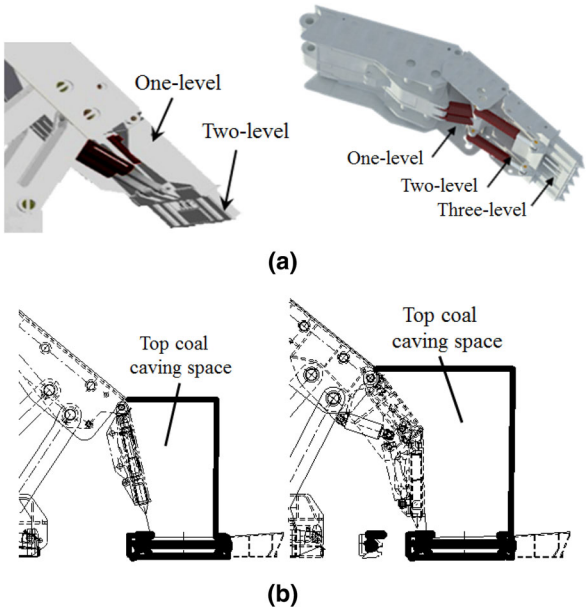


Fig. 7 Two types of top coal caving. **a** Top coal caving device contrast, **b** Top coal caving space contrast

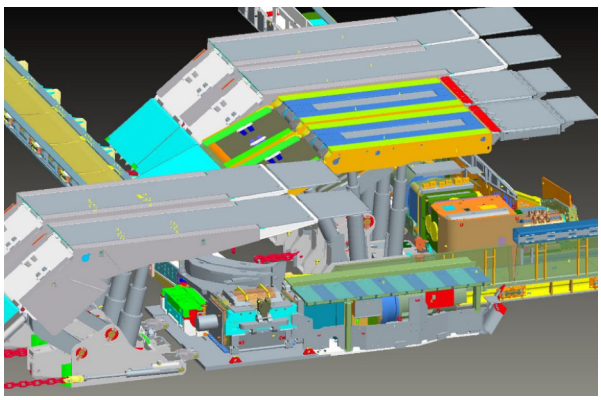


Fig. 8 Cross side-discharge scraper matching manner

such as the bottom heave, slippage, etc. The drawback would induce slanting, topple and fall, gliding of hydraulic supports, etc. In this respect, it is challenging to perform coupling stability control of hydraulic support and surrounding rock. The longwall mining system instability and coal gangue splashing menace the mining safety. The steep dipping seam mining has long been a challenge in global coal mining industry. In China, the steep dipping seam is evenly distributed in each major mining site. The reported reserves and production account for 10%–20% of the total coal reserves and 5%–8% of the total coal output in the country. In addition, more than 50% of the steep dipping

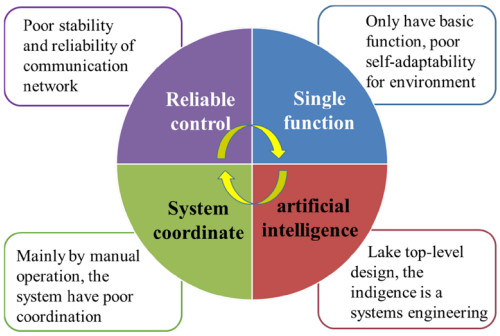


Fig. 9 Intelligent longwall mining key technical problems

seam mines are high-quality coking coal and anthracite coal. How to realize the stability coupling control of hydraulic support and surrounding rock in steep dipping working face restricts the safe and high-efficiency mining for steep dipping seam (Liu and Wang 2005; Luo 2015).

The final form of hydraulic support and surrounding rock instability in steep dipping face is the supporting failure and surrounding rock instability, which would induce surrounding rock accidents. Based on the coupling relationship between hydraulic support and surrounding rock, we analyze the mining pressure field distribution characteristics and the instability law of hydraulic support and surrounding rock, as shown in Fig. 10. We also examine the difference of supporting demand between steep dipping face and near horizontal or gentle dip face, and the steep dipping face needed 3D supporting for roof, floor and rib. The supporting device with self-supporting, next to pull, bottom to push and top beam squeeze is designed for steep dipping seam. In addition, we develop the hydraulic support with 3D preventing the spoil from splashing, which solves the instability problem of hydraulic support and surrounding rock.

To accommodate the steep dipping seam in Songzao coalmine with an average angle of 64° the working face adopts bow pseudo-inclined layout, and the rhombus hydraulic support is introduced to keep the constant roof distance, which realizes the double supporting function for sideway and roof surrounding rock.

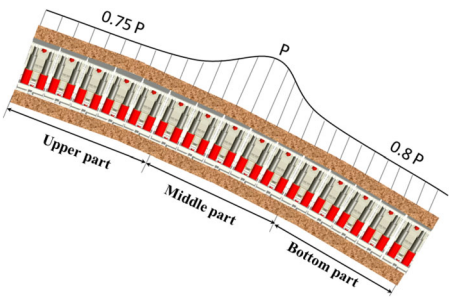


Fig. 10 Mining ground pressure distribution characteristics in steep dipping face

The largest mining angle is 55°, and the average coal seam thickness is 5.0 m of Fucheng coalmine in Inner Mongolia. Using longwall mining technology and equipment with high cutting and big angle, the working face output is 0.3 million tons per month, and the recovery ratio increases more than three times.

7 Conclusions

(1) The coupling relationship between hydraulic support and surrounding rock in terms of strength, stiffness and stability is the theoretical basis for surrounding rock stability control. Under the coupling action of mining pressure field and supporting stress field, the surrounding rock suffers dynamic instability. Although the hydraulic support does not change the final motion state of surrounding rock, it could influence the motion process in a way to protect the mining workers' working face.

(2) Based on the coupling principle between hydraulic support and surrounding rock, we develop a series of longwall mining technology and equipment, such as longwall mining technology and equipment with super cutting height for 6–8 m hard and heavy thick coal seam, fully mechanized caving mining technology and equipment with large mining height for 9–20 m hard and heavy super thick coal seam, which are used to build the system of longwall mining technology and equipment, and help fulfil safe, high-efficiency, and high-recovery mining for thick and super thick coal seams.

(3) To accommodate the unsteady 0.6–1.3 m thin coal seam, we invent the super large-scale magnification ratio strength hydraulic support and automatic mining pattern, which allow automatic and intelligent mining with supervisor and unmanned operation for thin coal seam.

(4) We develop the anti-skid and anti-collapse technology of self-supporting, next to pull, bottom to push and top beam squeeze for steep dipping hydraulic support and make a solid contribution to solving the stability control key technology of hydraulic support and surrounding rock for steep dipping working face.

References

Chen ZH, Feng JJ, Xiao CC, Li RH (2007) Fracture mechanical model of key roof for fully mechanized top-coal caving in shallow thick coal seam. J China Coal Soc 32(5):449–452

Gao J, He HT (2010) Application of fully mechanized full seam one passing mining technology to thick seam in Shendong mining area. J China Coal Soc 35(11):1888–1892

Gong PL, Jin ZM (2008) Mechanical model study on roof control for fully mechanized coal face with large mining height. Chin J Rock Mech Eng 27(1):193–198

Hargrave CO, James CA, Ralston JC (2017) Infrastructure-based localization of automated coal mining equipment. Int J Coal Sci Technol 4(3):252–261

Ju JF, Xu JL, Zhu WB, Wang QX, Hao XZ (2012) Strata behavior of fully mechanized face with 7.0 m height support. J Min Saf Eng 29(3):344–350

Liu JF, Wang GF (2005) Analysis on suitability of mini type hydraulic power caving support for deep inclined special thick seam mining. Coal Sci Technol 33(6):28–31

Liu CY, Yang JX, Yu B, Wu FF (2015) Support resistance determination of fully mechanized top-coal caving face in extra thick seam under multi-layered hard strata. J Min Saf Eng 32(1):7–13

Luo Y (2015) An improved influence function method for predicting subsidence caused by longwall mining operations in inclined coal seams. Int J Coal Sci Technol 2(3):163–169

Pang YH, Wang GF (2017a) Hydraulic support protecting board analysis based on rib spalling "tensile cracking-sliding" mechanical model. J China Coal Soc 42(8):1941–1950

Pang YH, Wang GF (2017b) Top-coal caving structure and technology for increasing recovery rate at extra-thick hard coal seam. J China Coal Soc 42(4):817–824

Pang YH, Liu XH, Ma L (2015) Key technologies of fully mechanized caving intelligent mining equipment in ten million tons of mines group. Coal Sci Technol 43(8):97–101

Sasaoka T, Karian T, H A, Shimada H, Matsui K (2016) Application of highwall mining system in weak geological condition. Int J Coal Sci Technol 3(3):311–321

Wang GF (2010) Innovation and development of completed set equipment and technology for high efficient coal mining face in underground mine. Coal Sci Technol 38(1):63–68

Wang GF (2013) Development of fully mechanized coal mining technology and equipment. Coal Sci Technol 41(9):44–48

Wang GF (2014) Theory system of working face support system and hydraulic roof support technology. J China Coal Soc 39(8):1539–1601

Wang GF, Pang YH (2015) Relationship between hydraulic support and surrounding rock coupling and its application. J China Coal Soc 40(1):30–34

Wang GF, Pang YH (2016) Shield-roof adaptability evaluation method based on coupling of parameters between shield and roof strata. J China Coal Soc 41(6):1348–1353

Wang YH, Guo DZ, Zhang HR, Shen BG (2006) Spatial distribution and application of coal resource potential in China. J Nat Resour 21(2):225–230

Wang GF, Liu JF, Ren HW (2011) Design and optimization of high seam-caving coal hydraulic support based on model of support and wall rock coupling. J China Coal Soc 36(1):145–151

Wang GF, Pang YH, Liu JF (2012) Determination and influence of cutting height of coal by top coal caving method with great mining height in extra thick coal seam. J China Coal Soc 37(11):1777–1782

Xu QY, Zhao YJ, Li YM (2015) Statistical analysis and precautions of coal mine accidents in China. Coal Eng 47(3):80–82