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Coal mine methane control cost and full cost: The case of the Luling Coal Mine, Huaibei coalfield, China

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ABSTRACT

Affected by the macroeconomic situation, the profits of Chinese coal production continue to decline. Coal mines are forced to increase their methane control investment to ensure safety in production as methane disasters are becoming more and more serious. It is necessary for coal mines to calculate the methane control cost and the full cost of each alternatives before mining to perform economic evaluations for choosing methane control measures and mining methods in such a grim climate for the coal industry. Of all the optional methane control measures and mining methods, the purpose of cost reduction in coal mines could therefore be achieved by choosing the most economical one. Based on the analysis of the methane control technologies of the second and the third level, the Luling Coal Mine in the Chinese Huaibei coalfield is taken as an example to propose a simplified method of calculating the methane control cost and the full cost before mining. In this method, the full cost is divided into the direct production cost, indirect production cost, business tariff and annex and period cost. The current methane control cost and full cost are calculated at the current price level, and then, the actual costs are calculated with a certain annual growth rate according to the engineering time. The methane control costs and the full costs of a working face in the Luling Coal Mine's second and third level are obtained, and the cost-cutting measures are provided. Despite of small economic benefit, most of the drained methane is used as domestic fuel or for electricity generation, which brings obvious environmental effects.

1. Introduction

With its rapid economic development, China has become the world's largest energy consumer (BP, 2011). Coal, as the lifeblood of economic development, accounts for 66.6% of the nation's total energy consumption (NBSC, 2014). Chinese coal production has increased significantly from 1835 million metric tons (Mt) in 2003–3680 Mt in 2013, an annual growth rate of 10% (BP, 2014). With the continued dependence on coal production, coal mining is expected to become increasingly challenging, as shallow reserves are exhausted and deeper and more gassy seams are mined (U.N. ECE and M2M, 2010). The deeper levels have increased methane pressure and methane content, which could lead to serious methane disasters (Pan et al., 2014). Fig. 1 shows the death toll proportions of all the accidents in 2013, and the methane disaster accidents account for 32.6% of the total death toll. For all coal mines, a common issue is how to control methane effectively and achieve safe and high-efficiency mining.

At present, countries around the world generally adopt the method of methane drainage to reduce the possibility of occurrences of methane disasters (Lou et al., 2013; Tao et al., 2014). Permeability is an important parameter that reflects the complexity of methane migration in the coal, and it is an important index to evaluate the feasibility of methane drainage (Zhang et al., 2014). The permeability of coal-bearing stratum in China is generally low, which seriously restricts the drainage and utilization of coal mine methane (Kang et al., 2010). Even so, Chinese scholars have made great achievements in coal mine methane control technologies through their unremitting efforts. Since the 1960s, several methods were investigated to strengthen methane drainage in the working

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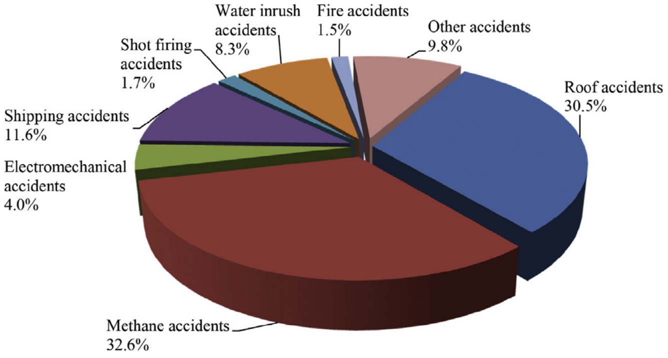

Fig. 1. The death toll proportions of all the accidents in the Chinese coal mines in 2013. Source: The online accident inquiry system of State Administration of Work Safety of China (SAWS, 2014).

seam for the issue of low permeability. The methods of crossing boreholes and bedding boreholes have been widely used (Yuan, 2004). To eliminate or weaken the outburst danger of adjacent seams, experiments on protective seam mining were conducted in Chinese coalfields, such as the Beipiao, Tianfu, Nantong, Zhongliangshan and Songzao coalfields. After many years of practical research, protective seam mining has been proven to be the most efficient and economical regional outburst prevention measure under the condition of coal seam group (Lama and Bodziony, 1998). With the development and application of fully mechanized mining technology, the method of comprehensive methane drainage has been adopted in China. The methane pre-drainage in the working seam, the pressure-relief methane drainage in the adjacent seams and the methane drainage in the gob are combined together in a coal mine, making full use of time and space to increase the amount of methane drainage.

Compared with the accomplishments of Chinese methane control technologies, the benefit of the current coal industry is not optimistic (Zhao et al., 2014). Since 2013, the Chinese coal industry has had the problem of structural overcapacity, leading to a rapid decline in coal price (BP, 2014; Mou, 2014). Meanwhile, coal mines are forced to increase their methane control investment to ensure safety in production as methane disasters are becoming increasingly serious. According to the fourth council conference report of China National Coal Association, a portion of coal enterprises are operating at a loss or have even gone bankrupt under the influence of both cost increases and price decreases. Taking Ordos City as an example, more than half of the coal mines were closed in 2013, and the gearing ratio of the state-owned coal mines was even over 50% by the end of 2013.

Facing the grim climate of the coal industry, extensive production mode of coal mines should be abandoned. Decision-makers of coal mines should strive to decrease costs by careful calculation and strict budget control. For Chinese coal mines, methane control costs account for a large proportion in the full costs of raw coal, and the figure for some coal mines could even reach 30%. If appropriate methane control measures could be chosen, they could not only reduce the methane control costs, but also optimize the mining methods and achieve the purpose of reducing the full costs. At present, the vast majority of Chinese coal mines do not perform economic evaluations before choosing methane control measures and mining methods, and they just discuss and make decisions on technology level according to geological prospecting materials (Cheng and Yu, 2007). Therefore, some coal mines might choose uneconomical methods, which could lead to high costs.

Much literature from home and abroad has discussed the cost of coal mining, and the finance sections in coal mines have also calculated the cost (Epstein et al., 2011; Li et al., 2009; NBSC, 2014). The costs they calculate are actual expenditures in a certain period of the whole coal mines, and they cannot be used to perform economic evaluations and decisions of engineering proposals as they are calculated after coal mining. Therefore, it is necessary for coal mines to calculate the methane control cost and the full cost before mining to perform economic evaluations for choosing methane control measures and mining methods. On this base, the purpose of cost reduction in coal mines could be achieved by choosing the most economical method of all the alternatives. In addition, calculating cost before mining can also help engineers to know more about the cost structure and distribution, thus more specific measures can be taken to reduce cost and achieve greater economic advantage.

Calculating cost before mining is the precondition for coal mines to conduct economic evaluations and decisions of methane control measures and mining methods, and the research of cost accounting is of great significance. It is difficult to calculate cost before mining as the production process of coal is comparatively complex, and little literature has comprehensively discussed the issue of calculating the methane control cost and the full cost before mining. Therefore, no appropriate method of calculating the methane control cost and the full cost before mining has been applied to Chinese coal industry. A simplified method of calculating the methane control cost and the full cost before mining is proposed in this paper. The Luling Coal Mine, a coal mine with the most serious methane disasters in the Chinese Huaibei coalfield, is taken as an example to calculate the methane control costs and the full costs of a working face in the second and the third level based on the analysis of the methane control technology.

2. Methane control technology of the Luling Coal Mine

2.1. General situation of the Luling Coal Mine

The Luling Coal Mine is an important coal industry base in eastern China. The major mineable seams of the Luling Coal Mine are seams 8, 9 and 10. The current mining and excavation activities are concentrated on the second level (elevation above −590 m) and continue the transition to the third level (−800 m to −590 m). There are 58 medium and large faults with over 20 m fault throws in the mine field. According to the complexity of the structural development, the mine field is divided into three parts, the eastern, the central and the western blocks (Fig. 2a).

Seams 8 and 9 of the Luling Coal Mine are prone to strong outbursts and have experienced 26 coal and gas outburst accidents between 1965 and 2002 because of complex geological structures and serious methane disasters. Some locations of the outbursts are marked in Fig. 2a. The Luling Coal Mine experienced an oversized coal and gas outburst accident on April 7, 2002, which was the second largest outburst in China and the third largest in the entire world. Table 1 lists the parameters for the thickness, firmness coefficient, permeability, methane pressure, methane content and initial speed of methane diffusion of seams 8, 9 and 10 in the second and the third levels. It is observed that seams 8, 9 and 10 all have the following characteristics: soft, low permeability, high methane pressure, high methane content and fast diffusion.

The roadway system of the second level is arranged in the floor of seams 8 and 9 and the roof of seam 10. The top-bottom sequence of coal mining is adopted because mining seam 10 first would destroy the roadway system. The second level mainly adopts the regional methane control technology of coal bed methane drainage, and it forms the methane pre-drainage method of double rock roadways crossing boreholes, which is suitable for the characteristics of seams 8 and 9. The methane pressure and content are

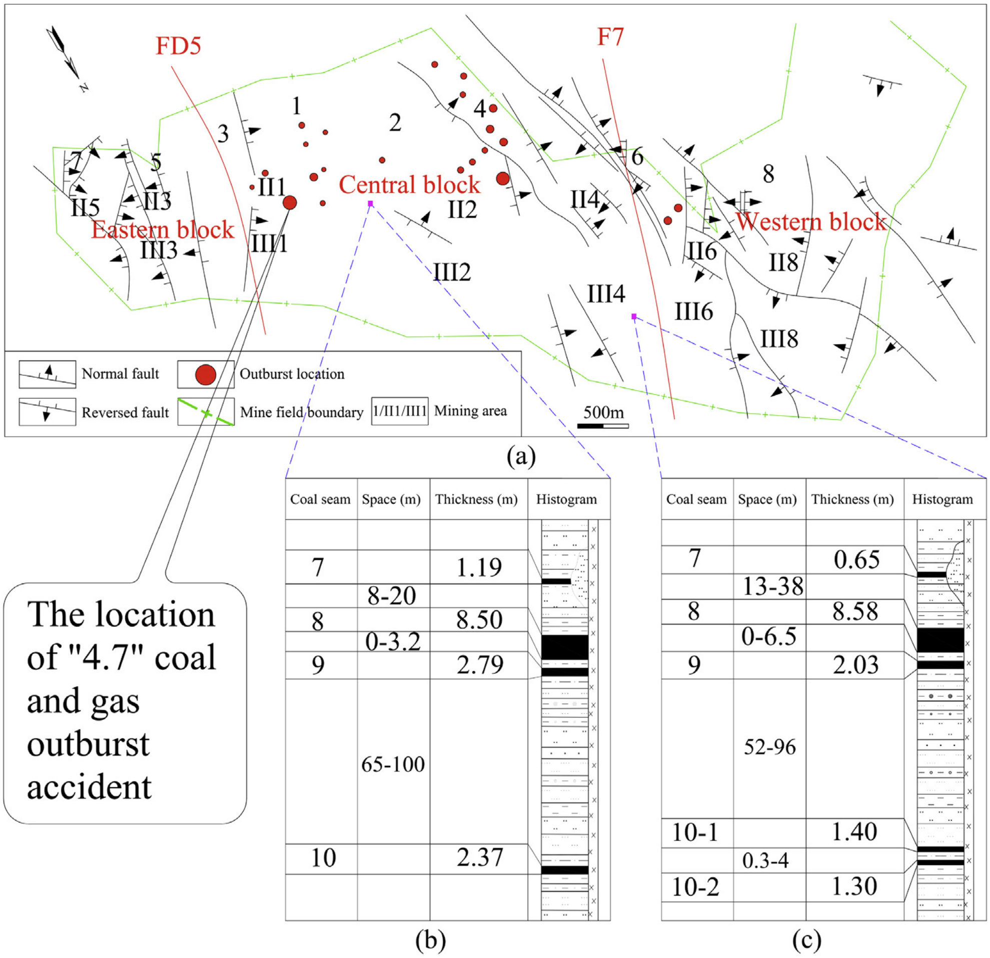

Fig. 2. The geographic position, faulted structure, and field division of the Luling Coal Mine and the stratigraphic columns of the second and the third level.

higher in the deeper third level, and the methane control method in the second level is no longer able to eliminate the outburst danger. The third level, therefore, adopts the methane control mode of protective seam mining and methane drainage up and down the mine. Seam 10 is a protective seam, and seams 8 and 9 are protected seams. Fig. 2b and Fig. 2c are the stratigraphic columns of the second and the third level, respectively.

2.2. Methane control technology of the second level

The process of the methane control technology for the second level in the Luling Coal Mine is illustrated in Fig. 3. Double rock roadways crossing boreholes are adopted to drain the methane and to reduce the outburst danger of seams 8 and 9, and then, bedding boreholes are constructed in the headentry of the top slice of seam 8 to further drain the methane of seam 8 to regionally eliminate the outburst danger of the top slice of seam 8. To solve the problem of gob methane flowing to the working face and accumulating in the upper corner in the process of mining the top slice of seam 8, buried pipes and high-level boreholes are used to drain the methane in the gob and the fissure zone. Through the mining of the top slice of seam 8, the outburst danger of seam 9 and the bottom slice of seam 8 are eliminated. Buried pipes are used to drain the methane in the gob when mining seam 9.

Table 1
Coal and methane comprehensive parameters of seams 8, 9 and 10 in the second and the third level.

Parameter	Second level		Third level	
	Seams 8 and 9	Seam 10	Seams 8 and 9	Seam 10
Thickness (m)	11.29	2.37	10.61	2.70
Firmness coefficient	0.11–0.46	0.11–0.46	0.11–0.46	0.11–0.46
Permeability (mD)	0.0007	0.0006	0.0006	0.0005
Methane pressure (MPa)	1.1–3.5	0.4–1.5	3.5–5.8	1.5–2.8
Methane content (m^3/t)	16.5	11.0	24.0	14.0
Initial speed of methane diffusion (mmHg)	30	16	34	25

Footnote: The firmness coefficient is a comprehensive index of coal's resistance to external damage. It can be obtained by striking the lump coal of 20–30 mm with a hammer and then measuring the amount of coal of grain size under 0.5 mm (see Chinese national standard GB/T 23561.12-2010). A higher value indicates that the coal is more stable and less prone to an outburst under the same gas pressure and crustal stress. The initial speed of methane diffusion is the methane emission rate of coal's initial exposure to the atmosphere. A higher value indicates that the coal is more seriously damaged and more conducive to outburst occurrences. A firmness coefficient less than 0.5 or an initial speed of methane diffusion greater than 10 mmHg is considered sufficient to initiate an outburst.

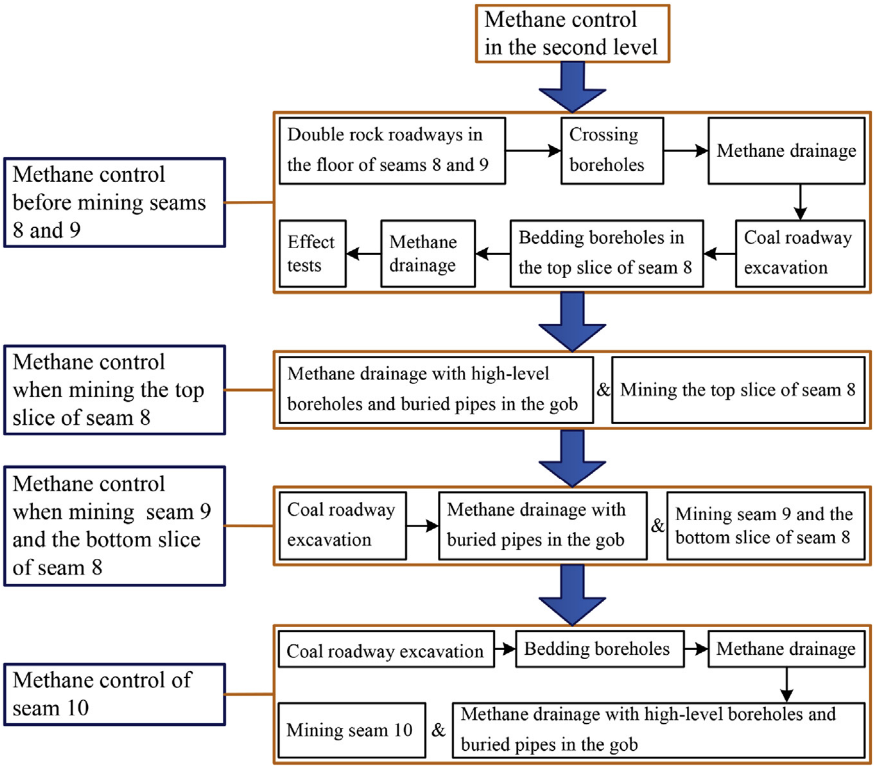

Fig. 3. Flow chart of the methane control technology of the second level working face.

Seam 10 in the second level has no outburst tendency. After the working face is formed, bedding boreholes are constructed in the headentry to drain the methane of seam 10 and to reduce methane emissions. Buried pipes and high-level boreholes are adopted to conduct methane control when mining seam 10. A working face of 1000 m of strike and 120 m of inclination is chosen to describe methane control engineering (Table 2). The methane control technology is illustrated in Fig. 4.

2.3. Methane control technology of the third level

The third level mines seam 10 to protect seams 8 and 9. The process of methane control technology is illustrated in Fig. 5. The large area crossing boreholes are adopted to drain the methane and to eliminate the outburst danger of the protective seam 10. One set of high-level boreholes is used in the process of mining seam 10 to drain the methane in the fissure zone. Meanwhile, buried pipes and surface well drillings are used to drain the methane in the gob and the fissure zone of seam 10.

Mining protective seam 10 unloads the pressure and increases the permeability of seams 8 and 9. Surface well drillings and another set of high-level boreholes in the tailentry of seam 10 can be used to drain the pressure-relief methane in the active period of methane migration. Protective seam mining and pressure-relief methane drainage regionally eliminate the outburst danger of seams 8 and 9, making them meet the requirement of fully mechanized mining with sublevel caving. Buried pipes are used to drain the methane in the gob when mining seams 8 and 9.

The district sublevels of seam 10 are arranged continuously, leaving no coal pillar to realize the continuous protection in the inclination direction on seams 8 and 9. The protective range in the strike direction is delimited according to the pressure-relief angle of 60° and the inward movement distances of the open-off cut and terminal mining line are both $D = H \times ctg60^\circ = 85 \times ctg60^\circ = 49.1$ m. To ensure mining safety, regions without pressure-relief in seams 8 and 9, roughly 100 m in the strike direction, will not be mined. A first mining working face of 1000 m of strike and 120 m of inclination is chosen to describe the methane control engineering (Table 3). The methane control technology is illustrated in Fig. 6.

3. Cost calculation method of raw coal

3.1. Calculation method of the full cost

The Luling Coal Mine adopts the full cost method to perform cost accounting for raw coal (Epstein et al., 2011; Li et al., 2009). The full cost includes the direct production cost, indirect production cost, business tariff and annex and period cost. Direct production cost refers to the direct production consumptions of material, fuel and power costs and staff remunerations, divided into the direct methane control cost, mining and excavation cost and other engineering costs. Indirect production cost includes the depreciation cost, maintenance cost, safety cost, surface collapse cost, resource cost, repair cost and other costs (rental cost, conference cost, office cost, travel cost, business entertainment cost, etc.). A part of the indirect production cost is still used for methane control, such as the depreciation, rent, repair of methane control equipment, methane control design and scientific research funds. Business tariff and annex refers to the taxes and surcharges incurred during daily activities, including city maintenance and construction tax, resource tax, education supplementary tax, building tax and land use tax. Period cost refers to the fees directly charged to the profit or loss of the enterprises in the current period, including marketing cost, administration cost and financial cost. The composition of the full cost of raw coal is summarized in Table 4.

For ease of comparison, it is necessary to calculate the methane control cost and the full cost per ton of coal (defined as the unit

Table 2
Main methane control engineering of the second level working face.

Engineering name	Engineering situation	Engineering quantity
Double rock roadways in the floor of seams 8 and 9	The track roadway and the centralism roadway are constructed in the stable rock stratum at a distance of approximately 20 m from the upper seam 9. The interval of the adjacent drilling sites in the track roadway is 30 m, whereas it is 25 m in the centralism roadway. The length of a drilling site is 3.5 m.	2550 m of rock roadways
Crossing boreholes	Four rows of boreholes are constructed along the strike direction in each drilling site of the track roadway, and the array pitch of boreholes is 7–8 m. Each row has 10 boreholes, and the interval is 8 m. Five rows of boreholes are constructed along the strike direction in each drilling site of the centralism roadway, and the array pitch of boreholes is 5 m. Each row has 9 boreholes, and the interval is 5 m. The diameter of the boreholes is 94–100 mm. All of the boreholes end at 0.5 m above seam 8, and the borehole sealing length is over 8 m.	160,000 m of boreholes
Bedding boreholes in the top slice of seam 8	Two bedding boreholes are constructed every 5 m in the headentry. The diameter of the boreholes is 92 mm. The length of the boreholes is approximately 105 m, and the borehole sealing length is over 15 m.	42,000 m of boreholes
High-level boreholes in the top slice of seam 8	One high-level drilling site, with a length of 15 m, is constructed every 60–70 m in the tailentry. Each drilling site has 6 boreholes, ending at 15–20 m above seam 8 with an interval of 6–10 m. The diameter of the boreholes is 92 mm. The superseding length is 20 m, and the borehole sealing length is over 5 m.	225 m of drilling sites and 8280 m of boreholes
Buried pipes in the gob of seams 9, 10 and the top slice of seam 8	Laying pipes alternately in the gob from the tailentry to drain the accumulated methane in the gob and the upper corner.	2500 m of pipes and some tee joints, bampers, etc.
Bedding boreholes in seam 10	One bedding borehole is constructed every 5 m in the headentry. The diameter of the boreholes is 92 mm. The length of the boreholes is approximately 105 m, and the borehole sealing length is over 15 m.	21,000 m of boreholes
High-level boreholes in seam 10	One high-level drilling site, with a length of 15 m, is constructed every 60–70 m in the tailentry. Each drilling site has 6 boreholes, ending at 10–12 m above seam 10 with an interval of 6–10 m. The diameter of the boreholes is 92 mm. The superseding length is 20 m, and the borehole sealing length is over 5 m.	225 m of drilling sites and 8172 m of boreholes

methane control cost and unit full cost). The coal production of a working face includes two parts, mining and excavation. The mining reserves are calculated according to the following equation:

$$Q_r = L \cdot M \cdot h \cdot \rho \cdot k \tag{1}$$

where Q_r is the mining reserves, t; L is the minable length in the strike direction, m; M is the minable length in the inclination direction, m; h is the minable thickness, m; ρ is the apparent density of coal, t/m^3; and k is the recovery ratio, %.

The excavation reserves are determined according to the ratio to mining reserves, and the ratios of the second and the third level working face are 4.2% and 3.0%, respectively. Calculations show that the mining and excavation reserves of the second and the third level working face are 2.0414 Mt and 1.7910 Mt, respectively, as shown in Table 5.

A long period of time is required between preparing a working face and the end of mining. The engineering time of the second level working face is 154 months, while the third level is 72 months (Fig. 7). The current accurately obtained costs are based on the price level in 2014, but price crush and an increase in coal cost are objective facts (NBSC, 2014; Yang et al., 2012). It is inappropriate to

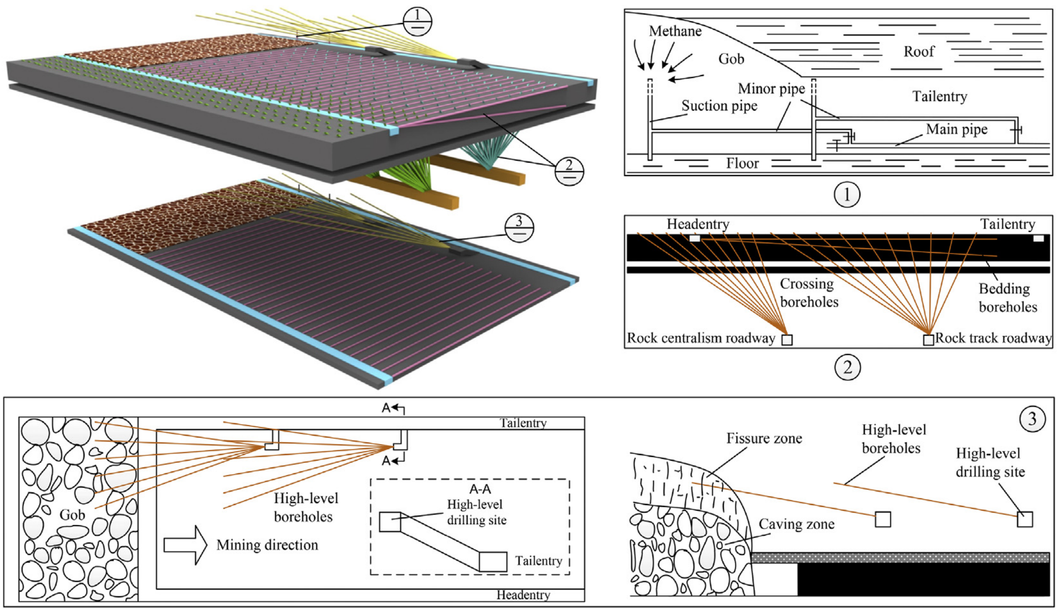

Fig. 4. Methane control technology of the second level working face.

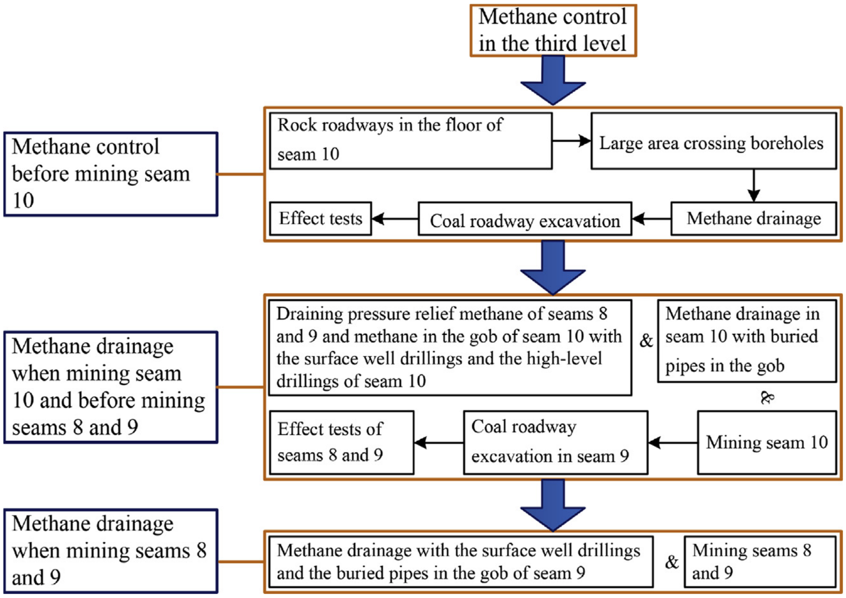

Fig. 5. Flow chart of the methane control technology of the third level working face.

Table 3
Main methane control engineering of the third level working face.

Engineering name	Engineering situation	Engineering quantity
Rock roadways in the floor of seam 10	Two methane drainage roadways are constructed in the stable rock stratum at a distance of 20–25 m from the upper seam 10. The interval of the adjacent drilling sites, with lengths of 3.5 m, is 30 m.	2530 m of rock roadways
Large area crossing boreholes of seam 10	The interval of the boreholes is 6 m in the coal roadway stripe, whereas it is 10 m in the internal district sublevel. The boreholes control the 150 m wide area. The diameter of the boreholes is 94–100 mm. All of the boreholes end at 0.5 m above seam 10, and the borehole sealing length is over 8 m.	144,000 m of boreholes
Surface well drillings	The surface well drillings are constructed along the strike direction, 50 m away from the tailentry in the inclination direction. The first surface well drilling is 50 m distant from the open-off cut, and the interval of the surface well drillings is 150 m.	7 surface well drillings
High-level boreholes in seam 10	One high-level drilling site, with a length of 15 m, is constructed every 60–70 m in the tailentry. Each drilling site has two sets of boreholes. Each set has six boreholes, ending at 10–12 m above seam 10 and 10 m under seam 9. The interval of the boreholes is 6–10 m, and the diameter of the boreholes is 92 mm. The superseding length is 20 m, and the borehole sealing length is over 5 m.	225 m of drilling sites and 18,180 m of boreholes
Buried pipes in the gob of seams 9 and 10	Same as the second level working face.	

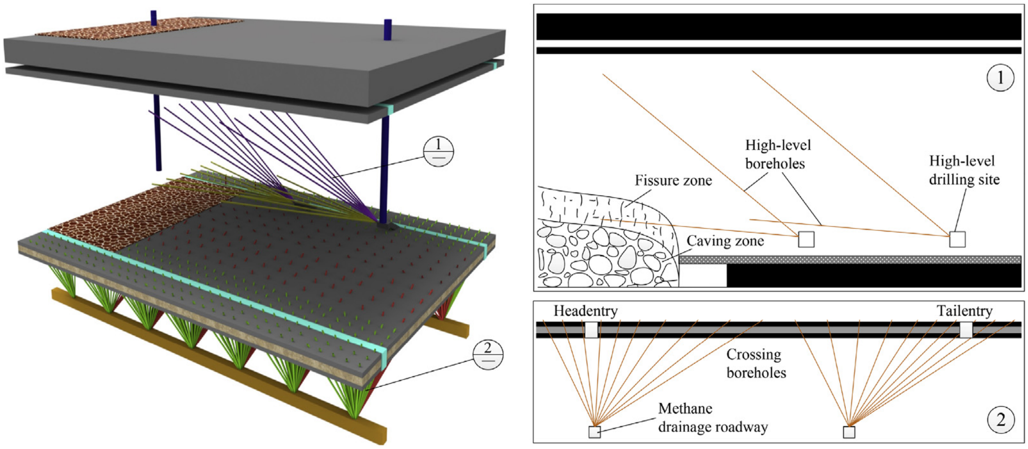

Fig. 6. Methane control technology of the third level working face.

Table 4
Composition of the full cost of raw coal.

Full cost	Classification
Direct production cost	Direct methane control cost, mining and excavation cost, other engineering costs (transportation and hoisting, ventilation, water drainage, electromechanics, other disaster control)
Indirect production cost	Depreciation cost, maintenance cost, safety cost, surface collapse cost, resource cost, repair cost, other costs
Business tariff and annex	City maintenance and construction tax, resource tax, education supplementary tax, building tax, land use tax
Period cost	Marketing cost, administration cost, financial cost

Table 5
Calculation of the mining and excavation reserves of the second and the third level working face.

Item	Second level			Third level	
	Top slice of seam 8	Seam 9 and bottom slice of seam 8	Seam 10	Seam 10	Seams 8 and 9
Length of strike (m)	1000	1000	1000	1000	900
Length of inclination (m)	120	120	120	120	120
Minable thickness (m)	2.00	9.29	2.37	2.70	10.61
Apparent density (t/m^3)	1.36	1.36	1.36	1.36	1.36
Mining method	Blasting mining	Fully mechanized mining with sublevel caving	Fully mechanized mining	Fully mechanized mining	Fully mechanized mining with sublevel caving
Recovery ratio (%)	94	85	94	94	85
Mining reserves (Mt)	0.3068	1.2887	0.3636	0.4142	1.3246
Summation (Mt)	1.9591			1.7388	
Ratio of excavation reserves to mining reserves (%)	4.2			3.0	
Mining and excavation reserves (Mt)	2.0414			1.7910	

calculate the full cost merely based on the 2014 standard. A certain model should be adapted to calculate the actual costs.

The annual cost growth rate of the Luling Coal Mine is determined to be 3% according to the data of production cost in the last 5 years. Therefore, the model, on average, distributes the cost calculated in the 2014 standard to each year of engineering time and then calculates the actual costs of each year with the annual growth rate of 3%. On this basis, the total actual cost could be easily obtained by summating all the actual costs of each year. For example, if the cost in the 2014 standard is 6 K (K is a coefficient) Yuan and the engineering time is 4 years (2015–2018). We distributes the cost into 4 parts, which is 1.5 K Yuan per year. Then we calculate the actual cost in 2015 with the growth rate of 3%, so the actual cost in 2015 is 1.5 K × 1.03. Similarly, the actual costs in 2016, 2017 and 2018 are $1.5K \times 1.03^2$, $1.5K \times 1.03^3$ and $1.5K \times 1.03^4$, respectively. Therefore, the total actual cost is $1.5K \times (1.03+1.03^2+1.03^3+1.03^4) = 6.4637K$. It is worth mentioning that, although the maintenance cost and safety cost are extracted

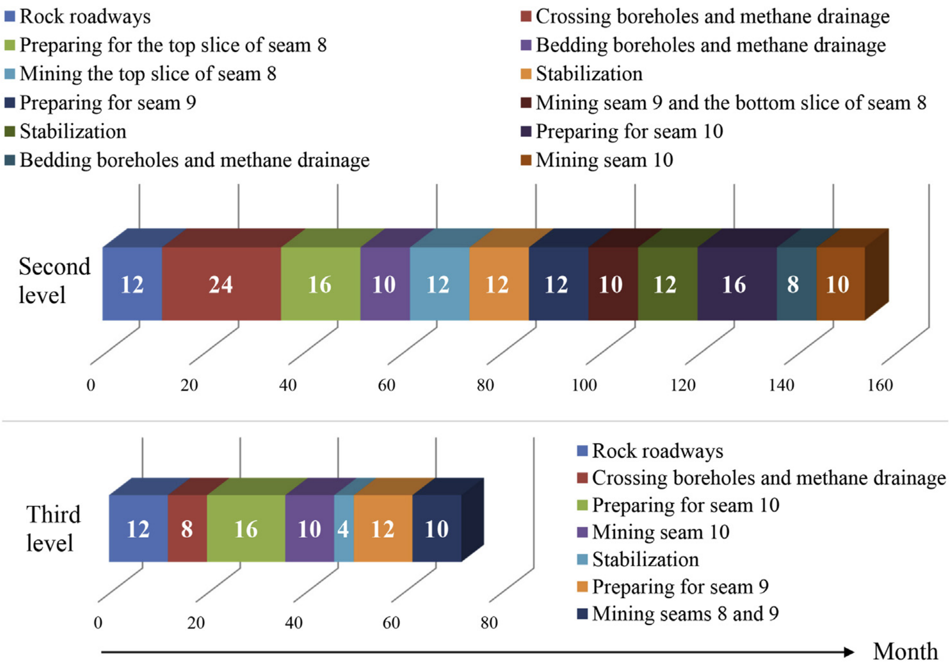

Fig. 7. Engineering time of the second and the third level working face.

according to the output of raw coal, these costs are used for coal production and are bound to increase with the price crush, merely remaining unchanged over a period of time.

If the start time of the engineering is 2015, the ratio of the actual cost to the cost in the 2014 standard can be easily obtained by the following equation:

$$A=\frac{k_2}{k_1}=\frac{1}{n}\sum_{i=1}^{n}1.03^i=\frac{1.03^{n+1}-1.03}{0.03n} \tag{2}$$

where k_2 is the actual cost; k_1 is the cost in the 2014 standard; A is the ratio; and n is the engineering time, which is 13 years for the second level and 6 years for the third level. For the second level, A_1 is 1.2374, and A_2 is 1.1104 for the third level.

The calculation flow of the full cost is illustrated in the red dashed frame in Fig. 8.

3.2. Calculation method of the methane control cost

The methane control cost includes the direct methane control cost and indirect methane control cost. The direct methane control cost includes the main methane control engineering cost and other methane control engineering cost. The main methane control engineering refers to rock roadways, crossing boreholes, bedding boreholes, high-level boreholes, surface well drillings and buried pipes in gob. The other methane control engineering refers to basic parameter measurements of methane, supplement boreholes, methane control measures of rock cross-cut coal uncovering, local outburst prevention measures, effect tests, methane drainage and so on. As the other methane control engineering has too many items and its cost is difficult to calculate accurately, the other methane control engineering cost is taken as 15% of the main methane control engineering cost. Therefore, the direct methane control cost is 1.15 times the main methane control engineering cost. The indirect methane control cost includes the depreciation, rent, repair of methane control equipment, methane control design and scientific research funds. The indirect methane control costs of the second and the third level working face in 2014 are both 10.7 Yuan/t according to the production cost data of the Luling Coal Mine. The sum of the direct methane control cost and indirect methane control cost is the total methane control cost in the 2014 standard. The actual methane control cost should also be calculated as the cost in the 2014 standard is not actual. The main methane control engineering cost is mainly incurred before coal mining, while the indirect methane control cost is in the process of coal mining. The coefficient A calculated above could also be adopted to calculate the actual methane control cost as its precision meets the requirements. Therefore, the methane control cost in the 2014 standard multiplied by A is the actual methane control cost. The calculation flow of the methane control cost is illustrated in the blue dashed frame in Fig. 8.

4. Calculation of the methane control cost and the full cost

4.1. Calculation of the methane control cost

The calculation of the main methane control cost is the key to obtaining the methane control cost. The main methane control cost can be obtained by multiplying the engineering quantity in Tables 2 and 3 by the unit price, and then, the direct methane control costs of the second and the third level working face are gained, as shown in Table 6 and Table 7.

Summarizing the costs and multiplying by A_1 or A_2, the unit methane control costs of the second and the third level working face can be obtained, as shown in Table 8.

The methane drainage cost per cubic meter is also an important index for evaluating the economy of methane control. The regions of methane drainage in the second level working face are 1000 m of strike, 125 m of inclination in seams 8 and 9, and 1000 m of strike and 120 m of inclination in seam 10. The regions of methane drainage in the third level first mining working face are 900 m of

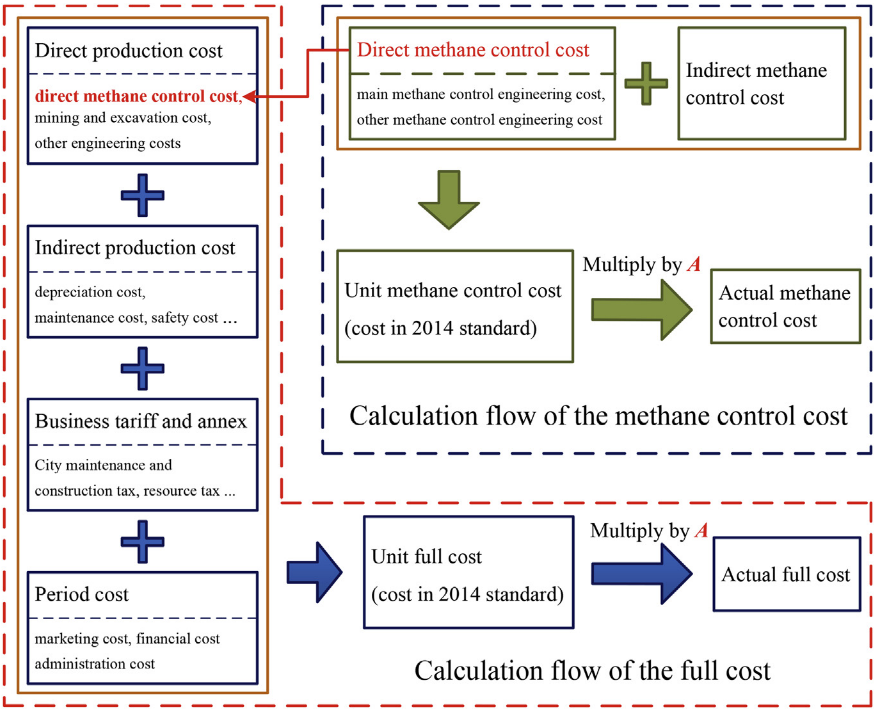

Fig. 8. Calculation flow of the methane control cost and the full cost.

Table 6
Direct methane control cost of the second level working face.

Engineering name	Engineering quantity	Unit price	Cost (Yuan)
Double rock roadways in the floor of seams 8 and 9	2550 m	12,000 Yuan/m	30,600,000
Crossing boreholes	160,000 m	250 Yuan/m	40,000,000
Bedding boreholes in the top slice of seam 8	42,000 m	160 Yuan/m	6,720,000
High-level drilling sites in the top slice of seam 8	225 m	12,000 Yuan/m	2,700,000
High-level boreholes in the top slice of seam 8	8280 m	250 Yuan/m	2,070,000
Buried pipes in the gob of seams 9, 10 and the top slice of seam 8	3 layers	400,000 Yuan/layer	1,200,000
Bedding boreholes in seam 10	21,000 m	160 Yuan/m	3,360,000
High-level drilling sites in seam 10	225 m	12,000 Yuan/m	2,700,000
High-level boreholes in seam 10	8172 m	250 Yuan/m	2,043,000
Summation of main methane control engineering cost			91,393,000
Direct methane control cost			105,102,000
Unit direct methane control cost			51.49

Source: Finance Section and Methane Control Office in the Luling Coal Mine.

Table 7
Direct methane control cost of the third level working face.

Engineering name	Engineering quantity	Unit price	Cost (Yuan)
Rock roadways in the floor of seam 10	2530 m	12,000 Yuan/m	30,360,000
Large area crossing boreholes of seam 10	144,000 m	250 Yuan/m	36,000,000
Surface well drillings	7 well drillings	1,500,000 Yuan/well drilling	10,500,000
High-level drilling sites in seam 10	225 m	12,000 Yuan/m	2,700,000
High-level boreholes in seam 10	18,180 m	250 Yuan/m	4,545,000
Buried pipes in the gob of seams 9 and 10	2 layers	400,000 Yuan/layer	800,000
Summation of main methane control engineering cost			84,905,000
Direct methane control cost			97,641,000
Unit direct methane control cost			54.52

Source: Finance Section and Methane Control Office in the Luling Coal Mine.

strike, 120 m of inclination in seams 8 and 9, and 1000 m of strike and 150 m of inclination in seam 10. Calculating with the residual methane content of 6.0 m^3/t, the amount of methane drainage in the second and the third level working face are 22.08 million cubic meters (Mm^3) and 32.46 Mm^3, respectively. The methane drainage costs per cubic meter are 7.11 Yuan/m^3 and 4.00 Yuan/m^3, respectively.

At present, most of the drained methane of the Luling Coal Mine is used as domestic fuel or for electricity generation, and the methane utilization should be a payback in the cost calculation. However, much investment (such as depreciation cost of power plant and methane storage tanks, staff remunerations, repair cost and taxation) is necessary to obtain the payback. Actually, the input and output of methane utilization could be regarded as a separate production system, and the drained methane is the raw material of the system. Therefore, the calculation model in this paper does not take the input and output of methane utilization into consideration for the simplification of the calculation. If the input and output of methane utilization are considered, the calculation results would not have a big difference as they are almost the same in the Luling Coal Mine.

4.2. Calculation of the full cost

The full cost is obtained by calculating and summarizing the costs of the items in Table 4. The direct methane control cost has been calculated above. The mining and excavation cost needs to be calculated in detail according to the specific engineering conditions, as shown in Table 9 and Table 10. According to the data of the Finance Section and Plan Section in the Luling Coal Mine, the other costs, usually calculated based on coal output, are summarized in Table 11. It is worth mentioning that, the actual counting process is extremely complex as the business tariff and annex is affected by taxable product, company location, saleroom, input tax and other factors. For example, the resource tax depends on the taxable product of an enterprise. The land use tax, city maintenance and construction tax depend on the company location. The building tax is obtained by multiplying the residual value of the house property by (70%–90 %) × 1.2 %, and the specific percent is determined by local government. The education supplementary tax is the same for all Chinese coal mines. To simplify the calculation model, the total business tariff and annex of the Luling Coal Mine in 2014 is divided by the output of raw coal, so the business tariff and annex is estimated to be 7.99 Yuan/t.

Summarizing the costs and multiplying by A_1 or A_2, the unit full cost of the second and the third level working face can be obtained, as shown in Table 12.

5. Discussion

5.1. Comparative analysis of costs

Table 13 lists the costs of the items constituting methane control and their proportions of the total methane control cost. Among the

Table 8
Unit methane control costs of the second and the third level working face.

Item	Second level working face (Yuan/t)	Third level working face (Yuan/t)
Direct methane control cost	51.49	54.52
Indirect methane control cost	10.70	10.70
Summation	62.19	65.22
Actual cost (times A_1 or A_2)	76.95	72.42

Table 9
Mining and excavation cost of the second level working face.

Item	Engineering quantity	Unit price	Cost (Yuan)
Coal roadway excavation of the top slice of seam 8	2190 m	6600 Yuan/m	14,454,000
Mining of the top slice of seam 8	306,800 t	75.84 Yuan/t	23,267,700
Coal roadway excavation of seam 9	2190 m	6000 Yuan/m	13,140,000
Mining of seam 9 and the bottom slice of seam 8	1,288,700 t	74.46 Yuan/t	95,956,600
Coal roadway excavation of seam 10	2190 m	6000 Yuan/m	13,140,000
Mining of seam 10	363,600 t	68.95 Yuan/t	25,070,200
Summation			185,028,500
Unit cost			90.64

Source: Finance Section and Methane Control Office in the Luling Coal Mine.

Table 10
Mining and excavation cost of the third level working face.

Item	Engineering quantity	Unit price	Cost (Yuan)
Coal roadway excavation of seam 10	2190 m	6000 Yuan/m	13,140,000
Mining of seam 10	414,200 t	82.74 Yuan/t	34,270,900
Coal roadway excavation of seam 9	2090 m	6000 Yuan/m	12,540,000
Mining of seams 8 and 9	1,324,600 t	62.05 Yuan/t	82,191,400
Summation			142,142,300
Unit cost			79.36

Source: Finance Section and Methane Control Office in the Luling Coal Mine.

Table 11
Unit costs of the second and the third level working face in addition to direct methane control, mining and excavation. (a) Unit direct production costs in addition to direct methane control, mining and excavation. (b) Unit indirect production cost. (c) Unit business tariff and annex and period cost.

Item	Second level working face (Yuan/t)	Third level working face (Yuan/t)
Transportation and hoisting	28.23	32.56
Ventilation	22.24	24.46
Drainage	12.82	15.86
Electromechanics	50.17	52.26
Other disasters control	18.56	20.04
Summation	132.02	145.18
Depreciation cost	7.50	7.50
Maintenance cost	15.00	15.00
Safety cost	13.36	13.36
Surface collapse cost	15.00	15.00
Resource cost	6.84	6.84
Repair cost	6.00	6.00
Other costs	60.00	60.00
Summation	123.70	123.70
Business tariff and annex	7.99	7.99
Period cost	42.50	42.50

Footnote: The total safety cost is 33.00 Yuan/t, 19.64 Yuan/t of which is the self-occupied part and is included in the direct production cost. Listed in the table is the remaining 13.36 Yuan/t.
Source: Finance Section and Plan Section in the Luling Coal Mine.

main methane control engineering, the rock roadway and surface well drilling have smaller constructional difficulty and higher security, and the cost proportions of these engineering for the third level are larger than those of the second level. Engineering with bigger constructional difficulty and lower security are crossing borehole, bedding borehole, high-level drilling site, high-level

Table 12
Unit full costs of the second and the third level working face.

Item		Second level working face (Yuan/t)	Third level working face (Yuan/t)
Direct production cost	Direct methane control	51.49	54.52
	Mining and excavation	90.64	79.36
	Transportation and hoisting, ventilation, drainage, electromechanics, other disaster control	132.02	145.18
Indirect production cost		123.70	123.70
Business tariff and annex		7.99	7.99
Period cost		42.50	42.50
Summation		448.34	453.25
Actual cost (times A_1 or A_2)		554.78	503.29

borehole and buried pipe in gob, and only high-level borehole in the third level has larger cost proportion compared with the second level. In addition, the third level has higher cost proportion of the main methane control engineering, which means less cost proportion is used for secondary engineering, and the engineering efficiency is higher. Therefore, methane control in the third level is superior to the second level in terms of security and efficiency.

Table 14 lists the unit methane control costs, the unit full costs, the methane drainage costs per cubic meter, the length of boreholes per ton of coal and the proportions of methane control cost to full cost of the second and the third level working face. The table shows that three terms of the costs of the third level working face are all lower than those of the second level working face, and only the length of crossing boreholes and the proportion of methane control cost are slightly more than those in the second level working face.

Although the threat of methane in the third level is more serious than that in the second level, the mode of protective seam mining and methane drainage up and down the mine has an advantage in terms of economic benefit, security and methane control efficiency. The methane control mode of the third level working face makes seams 8 and 9 meet the requirement of full-seam mining. The mining and excavation engineering is saved, and the whole engineering time is shortened, making the unit full cost 51.49 Yuan/t lower than that of the second level working face. If the cost accounting had been conducted before mining in the second level and the methane control measure and mining method in the third level had been chosen, the unit full cost would have significantly decreased. Thus, it can be seen that appropriate methane control measures could not only ensure safety in production and decrease the methane control cost but also significantly decrease the full cost.

Therefore, calculation of the methane control cost and the full cost of each alternative should be conducted before mining, and appropriate and economical methane control measures and mining methods should also be adopted to achieve the purpose of cost reduction. By comparing the costs of the second and the third level, it can be seen that the regional methane control mode of protective seam mining and pressure-relief methane drainage should be preferentially adopted under the condition of coal seam group.

5.2. Methane drainage benefit and utilization

Although it poses a major threat to coal mine safety, methane is also a clean and high-efficiency fuel (Creedy and Tilley, 2003; Flores, 1998). The energy released in the combustion of 1 m^3 of methane is 35.9 million Joules, equivalent to the combustion of 1.2 kg of standard coal. In the meantime, methane is also an intense greenhouse gas with a global warming potential of 25, i.e. 25 times of the environmental impact over carbon dioxide, in a 100-year span (Cheng et al., 2011; IPCC, 2007).

The emissions of the drained methane could waste a significant amount of clean energy and destroy the natural environment (Karacan et al., 2011; Moore, 2012). To make full use of the drained methane, the Luling Coal Mine has built two sets of ground permanent methane drainage systems and four sets of underground mobile methane drainage systems to implement separate methane drainage of high and low density methane. High density methane drained by the ground old system is used as domestic fuel, and low density methane drained by the ground new system is used for electricity generation. The methane drained by the underground mobile systems is released into the atmosphere as it is difficult to collect. The methane utilization mode of the Luling Coal Mine in 2013 is illustrated in Fig. 9, and the data of the Luling Coal Mine's methane drainage, utilization amount and utilization rate from 2003 to 2013 are plotted in Fig. 10.

Approximately 54.54 Mm^3 of methane is drained in the Luling Coal Mine's second and third level working face. Calculating with a utilization rate of 60%, the utilization amount is 32.72 Mm^3, which is equivalent to reducing emissions by 785.38 Mm^3 of carbon dioxide and 57.6% of the greenhouse effect compared to direct emission. Regardless of whether it is for civil use or electricity generation, utilization of the methane brings small economic benefit but obvious environmental effects.

Although the current methane utilization rate is up to 60%, the Luling Coal Mine is still carrying out some measures to enlarge the utilization rate. The main measures are as follows: 1) Develop protective seam mining technology. More methane would be predrained with protective seam mining technology, and thus less methane would be drained by the underground mobile systems and released into the atmosphere. 2) Upgrade the methane drainage systems. The ground new and old systems are operating under full loads, which cannot meet the requirements of the third level. The methane drainage capacity will be greater than 55 Mm^3 per year after system upgrade, therefore, there would not be extra methane being released into the atmosphere. 3) Diversify the utilization of drained methane. With the development of methane drainage, the amount of the drained high density methane would exceed the consumption of local residents. Therefore, the redundant methane will be used as industrial fuels, automobile fuels and for chemical industry. With these measures, the methane utilization rate of the Luling Coal Mine would reach 75% in the next 5 years.

5.3. Relationship between the methane control cost and the full cost

Cost calculations have also been conducted in a working face of three other coal mines in the Huaibei coalfield. The methane

Table 13
Costs and proportions of the items constituting methane control.

Item		Second level working face		Third level working face	
		Cost (Yuan/t)	Proportion (%)	Cost (Yuan/t)	Proportion (%)
Main methane control engineering	Rock roadway	18.55	24.10	18.82	25.99
	Crossing borehole	24.24	31.50	22.32	30.82
	Bedding borehole	6.11	7.94	0	0
	High-level drilling site	3.28	4.26	1.67	2.31
	High-level borehole	2.49	3.24	2.82	3.89
	Buried pipe in gob	0.73	0.95	0.50	0.69
	Surface well drilling	0	0	6.51	8.99
Summation of main methane control engineering		55.40	71.99	52.64	72.69
Other methane control engineering		8.31	10.80	7.90	10.90
Indirect methane control		13.24	17.21	11.88	16.41
Summation		76.95	100	72.42	100

Table 14
Comparison of the second and the third level.

Comparison item	Second level working face	Third level working face
Mining and excavation reserves (Mt)	2.0414	1.7910
Unit methane control cost (Yuan/t)	76.95	72.42
Unit full cost (Yuan/t)	554.78	503.29
Methane drainage cost per cubic meter (Yuan/m^3)	7.11	4.00
Length of crossing boreholes per ton of coal (m/t)	0.0864	0.0906
Length of bedding boreholes per ton of coal (m/t)	0.0294	0
Proportion of methane control cost (%)	13.87	14.39

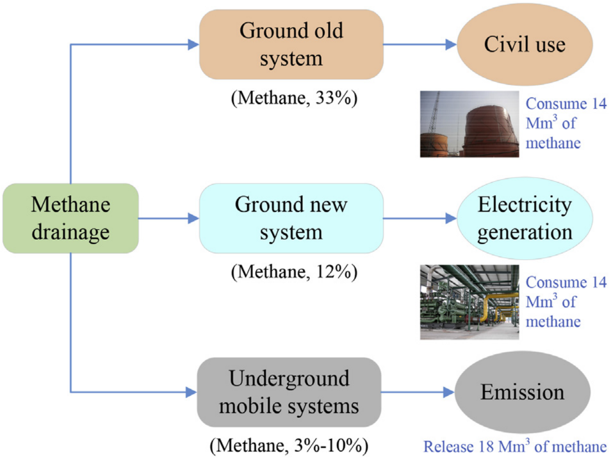

Fig. 9. Methane utilization mode of the Luling Coal Mine in 2013.

control costs, the full costs of different methane control measures and matched mining methods are summarized in Table 15. It is observed that for the same working face in a coal mine, method with low methane control cost also has low full cost. In addition, methane control cost accounts for a large proportion in the full cost, thus its size can indicate the quantity of the full cost to some extent. Therefore, for new coal mines with less cost data, the methane control costs could be calculated referring to neighboring coal mines with similar coal and methane occurrence, and the most economical method should be adopted according to the comparison of the methane control costs. But for coal mines with abundant cost data, both of the costs should be calculated for choosing the appropriate methane control measures and mining methods.

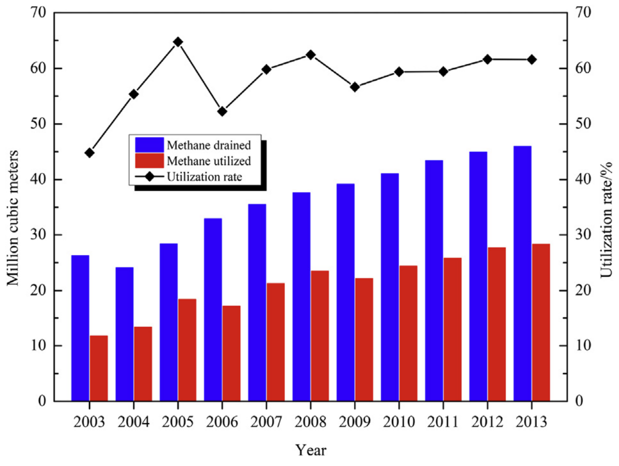

Fig. 10. Methane drainage, utilization amount and utilization rate of the Luling Coal Mine, 2003–2013.

5.4. *Feasibility of raw coal production*

It is generally accepted that the raw coal production is feasible only when the return on investment (ROI) is no less than 12%. According to this standard, the raw coal prices of the second and the third level working face should reach up to 621.35 Yuan/t and 563.68 Yuan/t, respectively. In fact, few Chinese coal mines can currently reach an ROI of 12%, and some mines even earn negative returns. Although few state-owned coal enterprises go bankrupt because of the state fiscal subsidy, the current state where the asset-liability ratio is increasing and mines are operating at a loss is not healthy and not a long-term policy. It is extremely urgent for coal mines to take appropriate methane control measures and mining methods and reduce the methane control cost and the full cost.

5.5. *Measures of reducing the methane control cost and full cost*

Safe and feasible methane control measures and mining methods should be drawn up according to geological prospecting materials, and the methane control costs and full costs of all the alternatives should also be calculated, thus the most economical method could be selected.

The arrangements of methane drainage roadways, boreholes and surface well drillings have a great influence on the methane control cost as well. After determining the methane control measures, it is important for engineers to focus on the engineering quantities to meet the requirements of eliminating outburst danger and do so without waste. Further measures to reduce the methane control cost are: (1) Optimize the cross-section and the support form to reduce the engineering quantity of methane drainage roadways; (2) Lay out the boreholes reasonably according to the radius of influence; (3) Optimize the borehole sealing process; and (4) Optimize the extraction system and reduce the cost of pipelines and supporting facilities.

In addition, coal enterprises should also strengthen cost management and focus on economy combined with technology as a strategy. The following strategies can be acted on: (1) Improve the management innovation and technological progress, advocate the innovative spirit of enterprise and improve the conversion rate of scientific research achievements; (2) Establish a grassroots cost accounting system to improve the awareness of employees; (3) Implement a budget control system and strengthen the target cost management; and (4) Assess the target cost and combine it with an incentive mechanism.

5.6. *Problems*

Actual coal mine production is always a process of coproduction and alternation of multiple mining and excavation working faces. The engineering time, engineering quantity and unit cost are

Table 15
Methane control costs and full costs of three other coal mines in the Huaibei coalfield.

Coal mines	Projects	Methane control costs (Yuan/t)	Full costs (Yuan/t)	Proportions of methane control cost (%)
Qinan Coal Mine	A	79.18	405.16	19.54
	B	84.62	418.29	20.23
	C	75.31	396.53	18.99
Xutuan Coal Mine	A	182.73	601.20	30.39
	B	70.04	469.01	14.93
	C	278.62	725.03	38.43
Zhuxianzhuang Coal Mine	A	96.79	453.82	21.33
	B	104.49	469.33	22.26

influenced by accidents, geological structures and national policies. In addition, the investment and the profit are difficult to calculate accurately because of the uncertain coal output and output time. To simplify the calculation model, this paper, therefore, takes a working face as an example to perform calculations and takes no account of the time value of money. The influence of large accidents, changes of geological structures and national policies are also left out of consideration. Although the simplified calculation model has some differences from the practical situation of a coal mine, the calculation method and idea of analyzing the methane control cost and the full cost still have a certain reference value for coal mines.

6. Conclusions

A simplified method of calculating the methane control cost and the full cost before mining is proposed in this paper. In this method, the full cost is divided into the direct production cost, indirect production cost, business tariff and annex and period cost. The current methane control cost and full cost are calculated at the current price level, and then, the actual costs are calculated with a certain annual growth rate according to the engineering time. The second and the third level working face of the Luling Coal Mine in the Chinese Huaibei coalfield is taken as an example to introduce the calculation method. Calculations show that the methane control costs of the second and the third level working face are 76.95 Yuan/t and 72.42 Yuan/t and the full costs are 554.78 Yuan/t and 503.29 Yuan/t, respectively. The comparative analysis of the second and the third level indicates that the adoption of appropriate methane control measures can reduce the methane control cost and the full cost. Other coal mines can refer to the cost accounting method proposed in this paper to calculate the methane control cost and the full cost to perform economic evaluations, thus the most economical method could be chosen to achieve the purpose of cost reduction.

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