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Safety line method for the prediction of deep coal-seam gas pressure and its application in coal mines

Liang Wang [a,b], Yuan-ping Cheng [a,*], Lei Wang [a], Pin-kun Guo [a], Wei Li [a]

[a] National Engineering Research Center of Coal Gas Control, China University of Mining & Technology, Xuzhou, Jiangsu 221116, China
[b] Post-Doctoral Research Station of Huaibei Mining Corporation Limited, Huaibei, Anhui 235000, China

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ABSTRACT

Gas pressure is an important index for evaluating the outburst risk and determining the gas content in coal seams. It is recommended to predict coal-seam gas pressure of the workface at deep levels before extending mining activities to deeper levels. According to the prediction results, measurements are taken for gas outburst prevention and control and for workload estimation. At present, regression methods are always used to process the numerous gas pressure data for prediction. Because there are many factors that influence the gas pressure which could lead to a deviation from actual values, the measured data do not possess basic conditions for regression methods; this can cause unexpected dangers if the methods are adopted.

Based on a statistical analysis of actual measured results of coal-seam gas pressure in a same geological section in certain coal mine, two symbol measured points are selected to make a line for prediction, i.e. safety line, and the other measured points should be below the line except the abnormal points due to the confined water. It has been successfully applied in numerous coal mines in China. Particularly, this method is analyzed in this paper for the case of the No. 8_2 coal seam in the Taoyuan coal mine in Huaibei coalfield, China. By comparatively analyzing the relationship between gas pressure and depth from surface using regression methods, it is found that the safety line method could lead to a better prediction for deep coal-seam gas pressure, and therefore promote early warning ability and mining safety.

1. Introduction

Since the first reported coal and gas outburst occurred in the Issac Colliery, Loire coal field, France, in 1843 (Lama and Bodziony, 1996), this type of disaster has been recognized worldwide as a potentially fatal and major hazard during the mining of gassy coal seams (Wold et al., 2008; Cao et al., 2001). Globally, the frequency and intensity of outbursts in China are the most severe (Cao et al., 2001). In the 2008 report of National Coal Mine Accident Analysis, coal and gas outburst accidents became the dominant gas disaster in coal mines in China, and the number of accidents and deaths accounted for 58.82% and 51.50% among all gas accidents respectively (State Administration of Coal Mine Safety, 2009).

The outbursts are dynamic, energetic events that may result in the projection of fragmented coal and the rapid release of gases from the working face (Wold et al., 2008). Outbursts are usually caused by many factors such as geological factors, gas pressure and coal physical properties (Yu, 1992; Lama and Bodziony, 1996, 1998; Beamish and Crosdale, 1998; Wold et al., 2008; Wu et al., 2009). As a basic parameter that determines the coal seam gas content and the potential energy of outbursts (William and Steven, 1998), the coal seam gas pressure is very significant in the study and evaluation of gas reserves, gas emission, gas flow, gas extraction and outburst (Xu et al., 2006; Cheng et al., 2009; Liu et al., 2009; He et al., 2010; Zhang and Lowndes, 2010). Gray (1980) and Paterson (1986, 1990) considered outbursts were driven mainly by gas pressure. In China, the coal seam gas pressure is a major index for evaluating the outburst risk of coal seams. According to the National Work Safety Industry Standards of China (AQ1024-2006, AQ1026-2006), the gas content in the controlled region must be maintained below 8 m^3/t or the gas pressure must be maintained below 0.74 MPa. The initial coal gas content and pressure should be measured in the new level and the new mining area of low gassy mines and when the mining area depth is increased by 50 m in highly gassy or outburst-prone mines.

The outburst tendency has been shown by Hargraves (1983) and Zhang (1992) to increase with depth and the advance rate of mining. And with an increase in mining depth, the coal seam gas pressure increases. Thus, gas disasters are becoming more serious as several shallow and non-outburst coal seams are gradually becoming outburst coal seams. Nowadays, there are 80 coal mines in China with mining depth reaching over 800 m, and the mining depth extends at the speed of 10–50 m every year. The techniques

* Corresponding author. Tel.: +86 516 83885948; fax: +86 516 83995097.
E-mail addresses: liangw1982@126.com (L. Wang), ypc620924@163.com (Y.-p. Cheng).

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used for gas outburst prevention and control should be suitable for underground coal mines, and all the techniques and workload are estimated according to the prediction results of the gas pressure and content. Scholars have conducted many studies on the relationship between the gas pressure and depth from surface for many years (First research room of coal institute in Liaoning Province, 1974; Mamunya, 1975; Xian and Xu, 1993; Lian and Li, 2008), and most of them used the method of one-dimensional linear or polynomial regression to derive experiential rules based on measured coal gas pressure data and specific geological conditions of mining areas. Because there are many factors that influence the gas pressure which could lead to deviations from the actual values, these measured data do not possess the basic conditions for regression methods, which can lead to unexpected dangers if adopted.

Based on a statistical analysis of actual measured results of coal-seam gas pressure in a same geological section in certain coal mine, two symbol measured points are selected to make a line for prediction after abnormal measured points are excluded due to confined water and other factors, i.e. safety line. Nowadays, the safety line method is successfully used in numerous coal mines in China, and it has proven to be reasonable and credible. It is believed to provide a safe and reliable basis for gas control in deep levels and assure mining safety.

2. Principle and requirements for gas pressure measurement

2.1. Principle of gas pressure measurement

The direct measurement method for the underground coal seam gas pressure involves the process of exposing coal seams by drilling, the installation of measurement instrumentation and the borehole sealing, and measurement of the gas equilibrium pressure at the place of exposure using the natural infiltration principle of gas. Concretely, while drilling the penetration borehole, a loose circle with numerous fissures can be formed around the borehole by the disturbance of drill pipe. After sealing the borehole and the loose circle, the pressure measurement room appears in the coal seam, where gas flows continuously from the infinite surrounding coal mass, and the pressure transfers to the measuring device along the pipe, which ensures supplementary gas for the loss due to the drilling process and the solidification period (usually 24 h). The pressure finally reaches the original coal seam gas pressure, as shown in Fig. 1.

For the hole sealing materials, solid material (including yellow mud or clay, shown in the left part of Fig. 1) and liquid material (including mucus, shown in the right part of Fig. 1) sealing methods are used in the direct measurement methods for the gas pressure. When the solid material sealing method is used, less equipment and simpler devices are needed, and the cost is low. However, it is only suitable for drilling openings in a rock roadway and requires less fractured hard rock, and the sealing length is short. It cannot be used to seal the loose circle to stop gas diffusion. The liquid material sealing method, coordinated with aprons or capsules, is sufficient for sealing fractures and the loose circle around the borehole, but the sealing length is also short, the equipment costs are high, and it is difficult to recycle. Therefore, the cement mortar hole sealing method, which combines solid and liquid materials, is usually used. This method has the widest applicability, and it has become a National Work Safety Industry Standard in China, i.e., Direct Measurement Methods of Underground Coal Seam Gas Pressure in Coal Mines (AQ1047-2007).

When using the cement mortar hole sealing method, 24 h are required for cement solidification after sealing. During this time, much gas is emitted from the borehole, which results in pressure relief of the coal seam around the measurement room, and the pressure measuring device requires a long time interval to become stable. Thus, to increase the sealing effect, the sealing time and exposure time of the coal wall should be reduced to lessen the gas loss quantity. In addition, supplement gas can be injected to offset the gas loss quantity, such as CO_2, CH_4 and N_2.

2.2. Requirements of measurement location

The selection of the pressure measurement locations should abide by the following rules. The preferred locations are crosscuts and rock roadways, with dense rock and no faults, fractures or other geological structures near the measurement points. Borehole drilling should avoid aquifers, caverns, mining affection, gas extraction, and other man-made pressure relief influence areas. According to the National Work Safety Industry Standards of China (AQ1047-2007), the distance between the boreholes and these areas should not be less than 50 m. A sufficient sealing depth should be maintained in the boreholes (the crossing coal points of the penetration boreholes and bedding boreholes should be located outside the broken circle of the roadway). Penetration boreholes for measuring was considered to be adopt firstly, and length of which should be more than 15 m. Two measuring points should be selected in the same place, with a distance not less than 20 m in principle, and the final crossing coal points or gas chambers should be outside the scope of mutual influence.

3. Gas pressure prediction methods development

3.1. Distribution law of coal seam gas pressure

The magnitude of the gas pressure depends on the gas emission conditions after coal generation. Coal seam gas migrates from deep strata to the earth surface as a basic trend; thus, the gas pressure and content increase with depth. According to the results for coal seam gas pressure around the world, vertical zoning characteristics appear in coal seams which are divided into the gas weathering zone and the methane zone (Yu, 1992). In the gas weathering zone, the gas pressure and content are low, and the gas pressure value of the lower boundary is approximately 0.15–0.2 MPa. In the methane zone, gas pressure increases with depth, and the gas pressure gradient varies with geological conditions. In a same geological section, the gas pressure usually shows the same general value at

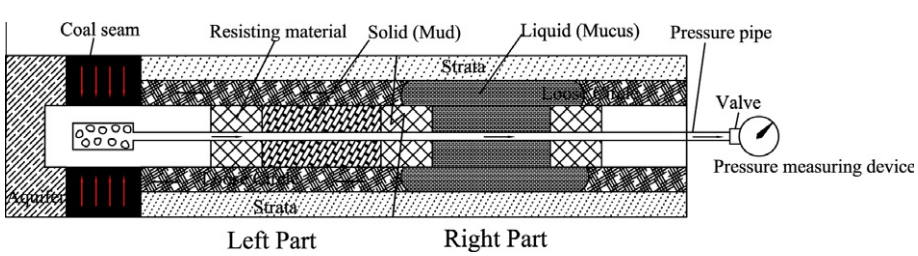


Fig. 1. Principle and methods of coal seam gas pressure measurement.

the same depth in identical coal seams, most of which have a linearly increasing law.

Fig. 2 and Table 1 show the maximum measured results for the coal seam gas pressure in different depth in some mining areas in China (Yu, 2005; First research room of coal institute in Liaoning Province, 1974).

Based on the data measured and the statistical analysis of outbursts in the mining area of Chongqing, Beipiao and Hunan (First research room of coal institute in Liaoning Province, 1974), it was found that the gas pressure distribution variation line with depth from surface was usually close to the hydrostatic pressure line (Line OC in Fig. 3), and the coal seam gas pressure had a limiting value, namely, the hydrostatic pressure value. They divided the gas pressure variation into two types. For type I such as in Chongqing, Hunan, the slope ω is smaller than 0.01 MPa/m (Line AD in Fig. 3), and the gap between the gas pressure and the limit value becomes larger with increasing depth. For type II such as in Beipiao, the slope ω is larger than 0.01 MPa/m (Line AB in Fig. 3), and the gap becomes smaller with increasing depth. The gas pressure variation keeps up with the line BC below the limit depth H_f, which is variant in different coal mines, usually deeper than 1000 m. The others include gas pressure measured in several typical coal mining areas, such as Zhengzhou, Xuzhou, and so on. The results were from different geological sections; therefore the slope ω was not close to the hydrostatic pressure line.

In practical calculations, the gas pressure growth curve can be approximated as a straight line within a certain depth (less than 1000 m) in the methane zone. Gas pressure is usually less than the hydrostatic pressure in the shallow level or no outburst-prone or lower outburst risk coal seams. In the deep level or serious outburst risk coal seams, gas pressure can approach or reach the hydrostatic pressure. Gas pressure variation keeps up with the hydrostatic pressure line below the limit depth. At the same time, the gas pressure may show a great deviation with the linear rule in some local regions with varying geological conditions, such as property of covered terrains change, the magmatic rock intrusion, and the opening of a major fault nearby.

3.2. Errors source of the measured data

Due to the gas occurrence, geological conditions, and boreholes sealing quality, pressure measured in field is close to but less than the real gas pressure in the coal seams. And there are lots of gas diffusion channels that are limited by location, material and technology, such as pressure relief areas, rock fractured zones, and loose circles and connecting valves of boreholes, which result in a lower measured gas pressure. At the same time, the hydro-geological conditions of Chinese coal fields are complicated, and the main coal-producing areas are the Carboniferous–Permian coal field in North China and the South Late Permian coal field, which belong to the karst hydro-geological type. The coal field of the Huang-huai plains is limited by quaternary alluvial water hazards. The process of drilling boreholes for gas parameter measurement inevitably passes through rich (or weak) aquifers. If effective measures are not taken to block the cracks, the water will affect the authenticity of the parameter data, even resulting in scrapped drilling, and the measured results with confined water are always larger than the real ones.

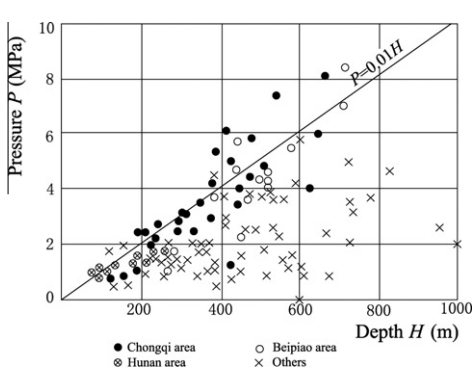


Fig. 2. Variation relation of coal seam gas pressure versus depth in different areas.

To judge whether the measured result is water pressure or not, a large number of former measured values must be compared, the effluent must be tested after the measuring device disassembled, and the pressure curve versus time must be compared with standards. In a coal seam with the same permeability, the gas pressure measured results change with time is generally consistent with the Gompertz curve or the Logistic curve. Large amount of gas swarms into borehole at the initial stage in coal seams with high permeability, thus the gas pressure variation curve rises rapidly (shown as the Gompertz curve). And in coal seams with low permeability, curve rises slowly (shown as the Logistic curve). Three stages can be found in both curves of pressure variation in Fig. 4 (Cheng, 1994).

3.3. Analysis of the present prediction methods

The production process generates a large amount of measured gas pressure values. Due to the complexity of geological conditions, it is difficult to find a unified law for gas pressure changes with depth from surface. Using the theoretical formula for pressure calculation requires taking into account many factors, and it is not commonly feasible for technical persons. There are many factors that influence the gas pressure, and measurement error is random, but each measured result at the same depth obeys the same distribution, usually the normal distribution, namely:

$$P_t \sim N(\mu, \sigma^2)$$

where P_t is the gas pressure, MPa; μ is the mean of random variables; σ^2 is the sample variance.

According to numerous measured results at the same elevation, the sample mean ($\bar{p}_t$) is calculated as

$$\bar{p}_t = \frac{1}{n}\sum_{t=1}^{n} p_t$$

where $\bar{p}_t$ is the sample mean of gas pressure; n is the amount of random variables.

Given a significant level (α), $100 \times (\alpha/2)$ points were recorded as $z_{\alpha/2}$ for the upside of the standard normal distribution:

$$P\left\{\left|\frac{\bar{P}_t - \mu}{\sigma/\sqrt{n}}\right| > z_{\alpha/2}\right\} = \alpha$$

where α is the sample significant level; $z_{\alpha/2}$ stands for $100 \times (\alpha/2)$.

In this equation, if μ does not change significantly, given the significance level (α), then the range of $\bar{p}_t$ should be in the range of $(\mu - z_{\alpha/2}\sigma/\sqrt{n}, \mu + z_{\alpha/2}\sigma/\sqrt{n})$, that is, $\mu - z_{\alpha/2}\sigma/\sqrt{n}$ and $\mu + z_{\alpha/2}\sigma/\sqrt{n}$ become the dividing line for whether the pressure changes.

With simple concepts and a convenient usage mode, regression methods can be used for description, control, forecasting and other related work. However, it is necessary that the predicted variable be continuous, and the residual value must be normal, independent and homogeneous. Nowadays, in production practice, gas pressure changes with depth from surface are predicted using a linear regression method at the same geological section. This method shows a significant linear regression effect and practical value when the measured data are not discrete. It considers all measured data, which can reveal the relationship of the gas pressure change with the depth in the methane zone. In addition, some scholars found that

Table 1
Variation of gas pressure gradient in some coal mining areas in China.

Location	Depth of the gas weathering zone (m)	Gas pressure gradient (MPa m^{-1})	Comparing with the hydrostatic pressure gradient (MPa m^{-1})
Chongqing	60	0.0098	<0.01
Beipiao	133	0.0113	>0.01
Hunan	36	0.0070	<0.01
Others	–	–	<0.01

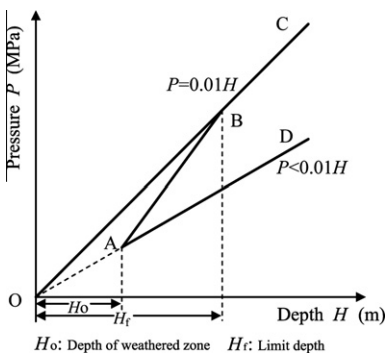


Fig. 3. Gas measured pressure variation curve versus time.

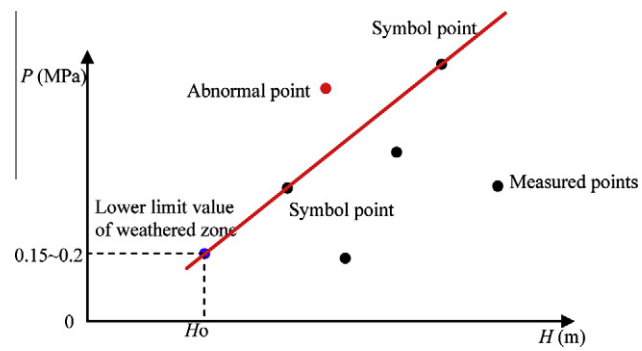


Fig. 5. Gas pressure prediction method: a safety line.

gas pressure increased with depth at first and then showed a decreasing trend according to the statistical analysis of historical measured data in individual mines and concluded that the gas pressure distribution law should be a polynomial regression (Lian and Li, 2008). This method is also unsafe for predicting deep gas pressure. When used, the deep pressure measured is usually lower than that at shallow depths. This situation usually occurs in the vicinity of special structures, such as the gap between larger open faults, which do not represent general laws.

Due to the lithology conditions of drilled boreholes, the sealing effect, and the uneven nature of coal seam gas occurrence, even measured results in the same geological unit are mostly scattered points. The measured results always have errors and a high dispersion of data, and they do not possess the basic conditions required for regression methods. Therefore, there are significant unexpected dangers when using either a linear regression or a polynomial regression for prediction. The regression method gives a number of deep prediction values that are lower than the true gas pressure, and the gas pressure curve thus greatly deviates from the extreme pressure curve. If the forecast data is used as a guide for taking measures to eliminate outburst risk, even if in theory it comes with a safe result (below 0.74 MPa and less than 8 m^3/t), the actual values may be beyond the requirement of the code. Therefore, this method should not be used for coal mines that require strong security and reliability.

3.4. New pressure prediction method: a safety line

In the recent production practice, we summarized variation law of the coal-seam gas pressure and presented an innovative graphic method to predict the coal-seam gas pressure at deep levels, i.e. safety line, which has been adopted in Huainan, Huaibei, Zhengzhou, Yangquan, Xuzhou and other mining areas, and the method uses statistical analysis for massive measured values of the gas pressure during the production process. The analysis basis of gas pressure must be in the same geological section, and the prediction limit depth should be less than 1000 m. First, abnormal measured points are excluded due to confined water, and then two true symbol points are selected to make the safety line. All the other points except the abnormal points are below the line, as shown in Fig. 5. The selection of the symbol points requires the consideration of the lower limit critical values of the weathered zone, in which the pressure values are 0.15–0.2 MPa. A selection is good if the safety line passes near the critical values. Otherwise, other points need to be chosen. If two suitable symbol points are not available, then one symbol point is chosen, and the safety line is made using the hydrostatic pressure

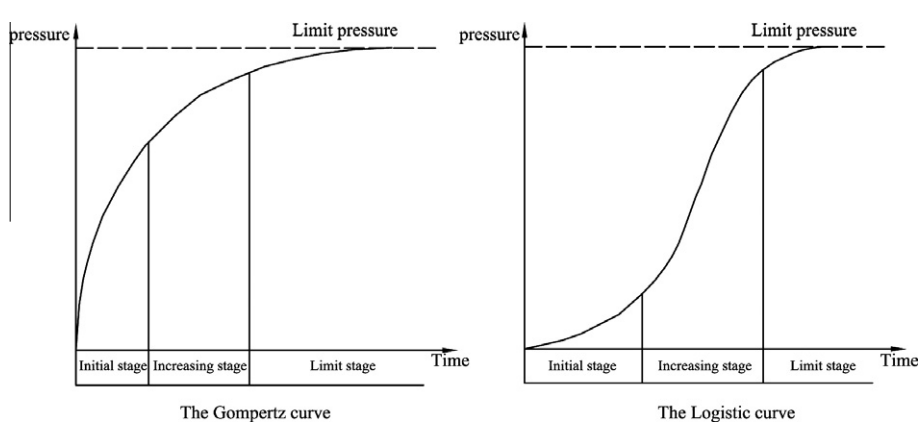


Fig. 4. Two types of gas pressure distribution laws.

gradient (0.01 MPa/m) as the gas pressure gradient. All the work should take into account the lower limit critical values of the weathered zone and make sure that the measured pressure values are below the line, except for the abnormal points. It has been noted that some measured pressure values at deep levels are lower due to the pressure measurement environment and the quality of the sealing effect, which are inconsistent with the basic law and cannot be adopted as symbol points.

In addition, the gradient of the gas pressure with depth from surface should approximately follow the relationship described below. It generally varies in the range of 0.01 ± 0.005. In the methane zone, the gas pressure is usually less than or same to the hydrostatic pressure due to the small tectonic stress in the shallow level, and the pressure value is equal to 0.01 times of depth. However, at deep levels of the coal mine, the ground stress, including self-weight stress, tectonic stress and temperature stress, linearly increase with vertical depth, and the gas pressure can exceed the hydrostatic pressure. Thus, the pressure value can be up to 0.013–0.015 times of depth (Zhou and Lin, 1999; Hu and Lin, 2006). Gas pressure anomaly regions exist in individual concentrated stress and high stress concentration zones.

The safety line method obviously takes a more conservative approach than regression methods since it relies upon maximum values at depth, which can prevent the under-prediction of the gas pressure and provide a favorable basis for formulating gas control measures. When this method is used, some essential conditions must be obtained. It needs more than five real measured data points in different depth from surface except the lower limit critical value of the weathered zone. If the limit critical value was not measured, it can be considered to be 0.15∼0.2 MPa for calculating. And the more data points there are, the more accurate prediction results they would be. Along with the increasing number of the measured data points, when the actual measured gas pressure value is greater than the value calculated by the safety line method, the symbol points should be re-selected, and the prediction line should be revised in time.

4. Results and discussion

4.1. Introduction of the Taoyuan coal mine

The Taoyuan coal mine is located in North Yangzhai town, in the southern part of Suzhou City, Anhui Province, China. The F1 fault is its northern boundary, and the 10th exploration line is the southern boundary, which is adjacent to the Qinan coal mine. The west boundary is the No. 10 coal seam outcrop line, and the depth of the +823 m bottom contour horizontal projection of the No. 3_2 coal seam forms the boundary on the eastern side. The length of its strike is about 15 km, and the trend length is about 1.5–3.5 km. The coal field area is about 32 km^2. The Taoyuan coal mine was founded in 1983 and brought into production in 1995 with a design capacity of 0.9 million tons per year. After expansion construction in 2006, it achieved a comprehensive production capacity of 1.6 million tons per year.

The Taoyuan coal mine is a coal and gas outburst mine, and the No. 8_2 coal seam is an outburst coal seam. While drilling in the No. 8_2 coal seam during the production period, some power phenomena occurred frequently, such as drill-sticking and jet orifices. The gas pressure of the second level (depth from +543 m to +823 m) ranged from 2.43 MPa to 5.46 MPa, and the gas content ranged from 9.99 m^3/t to 15.84 m^3/t.

4.2. Measured results of gas pressure in the Taoyuan coal mine

The cement mortar hole sealing method was widely used in the Taoyuan coal mine, as shown in Fig. 6. All the boreholes were drilled across to the raw coal seam from the rock roadway or drilling field. To avoid the influence of confined water, the upwards boreholes were drilled without drilling through the roof of the coal seam.

During the mining process, a large number of gas pressure values were measured, which are shown in Table 2. Twenty-five measured points which were located in the same geological section were obtained during the production process. The greatest value was 4.5 MPa, which was measured in the No. 5 drilling field of the return airway for powder storage at a depth from surface of +772 m.

4.3. Predition of gas pressure at deep levels

To provide guidance for the gas control of deep levels, gas pressure prediction is urgently needed based on existing gas parameters. The relationship between the gas pressure and depth from surface of the No. 8_2 coal seam in the Taoyuan coal mine were analyzed using one-dimensional linear, polynomial, logarithmic exponentiation and index prediction. The results are shown in Fig. 7. According to the analysis, the minimum relative coefficient was 0.2946, and the maximum was 0.3863. These methods were not strongly correlated with the prediction of the gas pressure and should not be adopted.

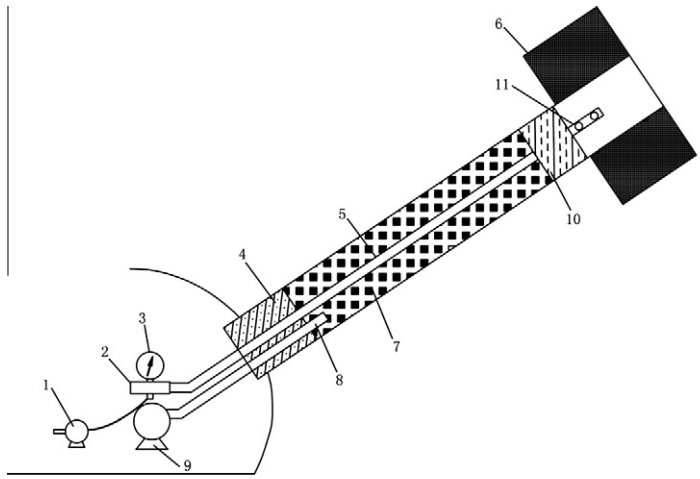
Fig. 8 shows the gas pressure prediction curves of the No. 8_2 coal seam in the production process in the Taoyuan coal mine, and simple linear regression, polynomial regression and safety line method were used for comparison. Obviously, abnormal measured points for the hydraulic pressure of confined water were excluded, which were the 1st, 2nd and 23rd points in Table 2. There was no water in the 3rd (+481 m, 1.76 MPa) or the 18th (+614.1 m, 3.2 MPa) boreholes in Table 2 when the pressure measuring devices were disassembled, and they were considered as the real gas pressure of the coal seam. When these two are linked as a strait line, the other points would be below the line, so these two gas pressure points were selected as symbol points.

As shown in Fig. 8, the actual measured gas pressure values of the No. 8_2 coal seam in the Taoyuan coal mine were very scattered. When simple one linear regression or polynomial regression was used, the predictive gas pressure was lower at deep depth, even lower than some actual values measured in field. These points were excluded, such as 3rd, 5th, 6th, 8th, 13th, 16th, 17th, 18th, 21st, 22nd and 25th According to the lower standard, gas control techniques estimated will bring a lot unexpected danger, which could not effectively ensure mining safety. Besides, the lower limit depth of the weathered zone of the No. 8_2 coal seam in the Taoyuan coal mine was found to be approximately +396 m, 50 m deeper than the actual weathered zone level of +343 m. All the results above showed that regression methods do not exactly reflect the gas pressure variation law.

When the safety line method was adopted, all the actual gas pressure values measured in field were below the line. The gas pressure curve equation of the safety line diagrams was $P = 0.0108 \times H - 3.4439$, and the weathered zone depth calculated using the equation was +333 m, which was almost the same as that of actual weathered zone. The gradient was 0.0108 MPa/m with a range of 0.01 ± 0.005 MPa/m, which agrees with the variation law of the deep raw coal seam. In addition, all gas pressure values measured in the later production process were near the safety line, which verified the safety and rationality of the safety line.

The gas pressure was calculated to investigate the gas occurrence law and prediction based on the safety line method, which is shown in Table 3.

In the development process for the second level roadway, the gas pressure was measured at levels up to 5.8 MPa at the depth +823 m in the Taoyuan coal mine, which was in the vicinity of the safety line,



1-Gas filling device; 2-Triple valve; 3-Pressure measuring device; 4-Wooden wedge; 5-Pressure measuring pipe; 6-coal seam;7-Cement mortar; 8-Injection pipe; 9-Injection pump; 10-Gripper; 11-Small hole

Fig. 6. Schematic diagram of the cement mortar hole sealing method.

Table 2
Gas pressure measurement results of the No. 8_2 coal seam in the Taoyuan coal mine.

Number	Depth from surface (m)	Actual measured gas pressure (MPa)	Remarks	Number	Depth from surface (m)	Actual measured gas pressure (MPa)	Remarks
1#	+323	1.27	With hydraulic pressure	14#	+606.9	0.95	
2#	+543	3.65	With hydraulic pressure	15#	+579	0.85	
3#	+481	1.76		16#	+645	3.3	
4#	+470	0.30		17#	+621	3.2	
5#	+532	1.80		18#	+614.1	3.2	
6#	+532	1.40		19#	+639	0.4	
7#	+473	0.47	Located at unrecoverable area of No. 8_2 coal seam	20#	+749.9	2.1	
8#	+664	2.60		21#	+772	4.5	
9#	+543	0.13		22#	+784	3.3	
10#	+543	0.30		23#	+763.7	5.4	With hydraulic pressure
11#	+543	0.15		24#	+791.1	0.72	
12#	+438	0.43		25#	+763.7	3.7	
13#	+510.4	1.52					

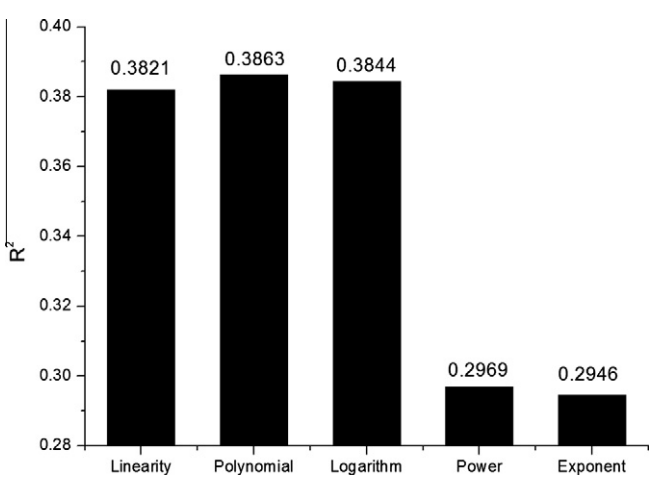


Fig. 7. R^2 analysis of correlation coefficients using different regression methods.

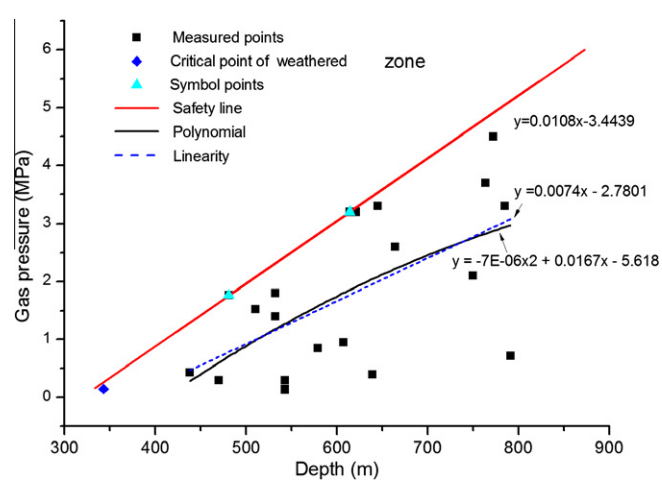


Fig. 8. Gas pressure prediction curves using different methods for the No. 8_2 coal seam in the Taoyuan coal mine.

as shown in Fig. 9, and verified the safety and rationality of the method. Because the measured result was higher than the value predicted by the safety line, it was necessary to modify the existing safety line and re-select the symbol points. Using the principles above to select the safety line symbol points, points (+481 m, 1.76 MPa) and (+823 m, 5.8 MPa) were selected to make the new safety line. The calculated lower limit depth of the weathered zone of the No. 8_2 coal

Table 3
The prediction values of the No. 8_2 coal seam gas pressure in the Taoyuan coal mine.

Number	Depth from surface (m)	Actual measured gas pressure (MPa)	Calculated value (MPa)	Remark
1#	+373		0.59	
2#	+423		1.13	
3#	+481	1.76	1.76	Symbol point
4#	+523		2.21	
5#	+573		2.76	
6#	+614	3.2	3.20	Symbol point
7#	+623		3.30	
8#	+723		4.38	
9#	+823		5.46	
10#	+873		6.00	

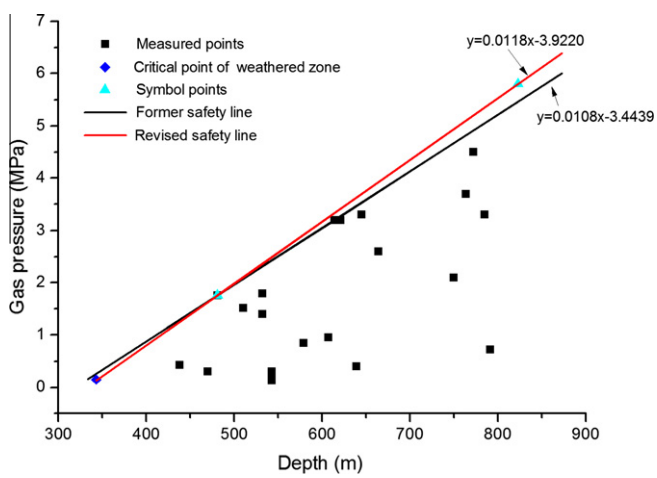


Fig. 9. Revised gas pressure prediction curves.

seam was approximately +345 m, which was almost the same as that of the actual weathered zone. The gradient was 0.0118 MPa/m with a range of 0.01 ± 0.005 MPa/m. And the gas pressure curve equation of the safety line diagrams was revised as $P = 0.\ 0\ 1\ 18 \times H - 3.9220$.

5. Conclusions

Gas pressure is an important index to evaluate the outburst danger and determine the gas contents in coal seams, and it is closely related to coal and gas outbursts. The techniques and workload used for gas outburst prevention and control are estimated according to the prediction results of the gas pressure and content. There are many factors that influence the gas pressure which could lead to a deviation from actual values, and the measured data do not possess basic conditions for regression methods. If regression methods are adopted, unexpected dangers would happen. The results from practice project in the Taoyuan coal mine showed that maximum relative coefficient was 0.3863 using regression methods. These methods were not strongly correlated with the prediction of the gas pressure and should not be adopted.

In this paper, the safety line method to predict gas pressure at deep levels is presented, and the results from practice project showed that gas pressure values measured in the later production process were near the line. The safety line method could reflect exact facts and is reasonable and credible. At present, the safety line method is used successfully in numerous coal mines in China, such as Huainan, Huaibei, Zhengzhou, Yangquan, Xuzhou and other mining areas. And it provides a safe and reliable basis for the gas control at deep levels to assure mining safety. When the actual measured gas pressure value is greater than the value calculated, the safety line must be revised.

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