Study on Application of a Five-step Approach to Gradual and Fast Coal Uncovering during Gassy Tunnel Construction

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Abstract: A five-step approach to gradual and fast coal uncovering during gassy tunnel construction is developed to address high risks and tunnel construction safety problems related to protracted coal uncovering. By examining the technical principle of gradual and fast crosscut coal uncovering technique, this paper concludes multi-parameter prediction is the key to this technique. It establishes multi-parameter prediction criteria for coal burst hazard and multi-dimensional arrangement of prediction holes; discusses how to set up a movable safety barrier zone and determine its scope; and develops a gradual and fast coal uncovering process for construction of gassy tunnels by which the burst-prone coal seam is uncovered through gradual excavation and advancement under the protection of the safety barrier. Application of this technique on the construction site of Huayan Tunnel shows this technique is easy to apply, economical and safe and significantly reduces the time spent on coal uncovering.

1. Introduction

In recent years China's transport infrastructure development has been moving toward mountain areas in the west of the country where geological structures are complex. Endowed with abundant coal resource, the southwestern mountainous area is one of China's major coal mining areas. Moreover, this area hosts coal seams bearing high content and saturation gas and is one of China's major mining areas for coal bed gas [1]. However, such risks as gas explosion and coal/gas burst exist when the tunnel passes through coal measure strata. In particular, during coal uncovering highly likely gas incidents will cause significant casualties and property losses. Consequently, safe and efficient coal uncovering for gassy tunnels is of significance to tunnel construction safety and meeting construction schedule [2].

Uncovering a burst-prone coal seam in a mine susceptible coal and gas bursts is a challenge in workplace safety and a bottleneck in mining arrangement because such uncovering is at the highest risk of burst and takes a long time. Depending on coal uncovering faces in geologically different coal fields, coal seams and crosscuts with different burst hazard levels, the following crosscut coal uncovering measures for burst prevention have been investigated: hydraulic flushing of holes; bleeder off hole; gas pre-drainage; metallic framework; straight deep hole full-section blasting; and direct application of shock blasting [3-5]. The burst-prevention coal uncovering technique for gassy tunnel construction was borrowed from the coal industry and initially used in constructing Jiazhuqing Gassy Tunnel [6-8]. Thereafter a construction process of hazard prediction, gas burst prevention and safe coal uncovering was developed as the burst prevention technique for gassy tunnel evolved, and successfully applied to construction of Jiazhuqing and Huayingshan tunnels [9-11]. Li Dong et al. studied coal uncovering...
techniques for large-section gassy tunnels by using hydraulic permeability improvement method which cut coal uncovering time by 50% compared to the expected time [12]. Ge Zhaolong et al. developed and successfully applied a new "five-step" gradual and fast crosscut coal uncovering technique in Songzao mine area in Chongqing [13].

This paper proposes a five-step gradual and fast coal uncovering technique for gassy tunnels to address high risks and tunnel construction safety problems related to protracted coal uncovering. This is accomplished by investigating the technical principle of gradual and fast crosscut coal uncovering technique; establishing multi-parameter prediction criteria for coal burst hazard and multi-dimensional arrangement of prediction holes; developing a gradual and fast coal uncovering process for construction of gassy tunnels; and applying the technique to construction of Huayan Tunnel.

2. Technical Principle of Five-step Gradual and Fast Coal Uncovering Technique for Gassy Tunnels

The key to the Five-step Gradual and Fast Coal Uncovering Technique for Gassy Tunnels is to eliminate or mitigate burst hazard based on reliable prediction and inspection by taking small steps to avoid drastic and excessively fast construction, reduce the effect of vibration on coal seam and preclude various inducements of burst. Its main feature is the division of the entire coal uncovering process into 5 steps. First, drill an advance geological probing and prediction hole at the pillar when the working face is 10m in normal distance from the coal seam to predict whether gas exceeds limits; if not, advance to the pillar 5m from the coal seam; if yes, drill advance bleeder off holes and eliminate burst hazard before advancing to the pillar 5m from the coal seam. This step is repeated when advancing to the pillar 3m and 2m from the coal seam. Finally, if it is confirmed that there is no hazard, the burst-prone coal seam is gradually uncovered by long-distance blasting. Each round must be under reliable protection of a safety barrier. When the burst hazard level is high making the barrier unreliable, stop advancing, drill additional advance holes or extract the gas in advance to eliminate burst hazard before proceeding with construction in steps. Each step shall be safe and reliable so as to complete the whole coal uncovering works. Use of large-scale shock blasting to uncover a thick pillar in a one-off manner shall be avoided. Drastic operation shall be prevented. This is because violent vibration resulting from shock blasting makes rock mass abruptly deform under compression shortly prior to swelling deformation which tends to induce coal and gas burst. Data from tests in a mine south of Zhongliangshan by CCRI Fushun Branch show the compressive deformation of rock mass subject to shock blasting is 2.4mm; 1h later, swelling deformation reaches 4.8mm as coal rock mass breaks to form cavity and open cracks, which tends to induce burst [14].

3. Construction Process of Five-step Approach to Gradual and Fast Coal Uncovering During Gassy Tunnel Construction

The gradual and fast coal uncovering technique cancels direct measurement of gas pressure and replaces single prediction with multi-parameter prediction using three-dimensional arrangement of prediction holes. The movable safety barrier zone established in this technique can eliminate burst and intercept burst outside the barrier. The working face is advanced gradually in multiple rounds involving small amounts of explosives for blasting to avoid activating burst-prone coal seam and avoid the use of shock blasting. In this way the coal seam is uncovered normally without any incident [15, 16].

3.1. Multi-parameter prediction

3.1.1. Desorption characteristics of gas in cuttings

In the gradual and fast coal uncovering technique, 65-87mm diameter advance prediction holes (also used as advance vent holes) may be drilled into the working face. After the hole enters the coal seam, 1~3mm size cuttings are obtained through sieve for each meter of the hole and measured by WTC gas burst instrument for the value of $K_1$. 

3.1.2. Indirect determination of gas pressure

As the tunnel passes through different coal measure strata, coal samples are taken from advance geological boreholes for coal bed gas parameter testing to establish the relation between the value of $K_1$ and gas pressure $p$:

$$K_1 = Ap^B$$

where $K_1$ is coal sample gas desorption characteristics index in $\text{m L/ (g.t)}$; $A$ is a factor $A = 3.35e^{2.93f}$; $B$ is a factor $B = 1.1736e^{-0.864f}$; $p$ is the calculated coal bed gas pressure in MPa; $f$ is coal seam firmness coefficient. The above equation is on a dry ash-free basis. The value of $K_1$ measured on tunnel construction site shall be corrected as appropriate, usually by dividing the measured value of $K_1$ by 0.75. While determining the value of $K_1$ in each step of coal uncovering, 500g coal sample 1~3mm in size shall be screened from cuttings from 1-2 boreholes for delivery to the lab to determine the value of $f$. Then the coal bed gas pressure is calculated using the above equation.

3.1.3. Comprehensive indicator

The comprehensive indicator $E$ is the ratio of measured cutting gas desorption characteristic value to measured $f$ value of coal seam. When burst occurs $E$ reaches critical value. The prediction and inspection indicator for coal uncovering is analyzed and determined as follows:

1) $f = 0.3~0.5$: when $E < 2$, the working face is without burst hazard; when $E \geq 2$, the working face is with burst hazard.

2) $f \geq 0.5$: when $E < 1.5$, the working face is without burst hazard; when $E \geq 1.5$ the working face is with burst hazard.

3.1.4. Determining coal burst hazard based on multi parameters

The method of predicting coal burst hazard based on cutting gas desorption characteristic indicator $K_1$ has been applied for over 10 years in Songzao mine area, a typical coal and gas burst-prone mine area in China. It can accurately predict burst hazard. Therefore, the prediction of coal burst hazard during coal uncovering for tunnel construction can be based on the value of $K_1$.

1) When the value of $K_1$ is less than critical value and drilling advance borehole does not encounter burst or other anomalies, the working face is determined to be without burst hazard regardless of the values of $p$ and $E$.

2) When the value of $K_1$ is greater than critical value, the coal firmness coefficient $f$ is greater than 0.5 and drilling advance borehole does not encounter burst or other anomalies, the hazard level of the working face shall be determined in conjunction with $E$.

3) When the value of $K_1$ approaches critical value, the hazard level of the working face shall be determined based on $p$ and $E$.

3.2. Three-dimensional arrangement of prediction holes

Depending on the angle between coal seam and the tunnel, advance prediction holes are drilled accurately in several steps. Generally coal uncovering for tunnel construction is executed in 5 steps, as shown in Fig. 1.

In each step many prediction and inspection holes are arranged in a three-dimensional grid in accordance with the hole density and control scope specified in the Coal Mine Safety Regulation. To avoid the effect of errors in individual holes, the number of advance holes may be increased to ensure the qualitative reliability of prediction and inspection holes as a whole. If the angle between the tunnel and
coal seam is small, the number of steps of drilling prediction holes shall be increased accordingly since the scope of burst prevention is larger.

Fig. 1 Standard distribution of prediction holes for crosscut coal uncovering

3.3. Establishment of a movable safety barrier zone
A safety barrier zone means a barrier used to prevent coal and gas burst as a result of drilling and blasting. Generally, the safety barrier shall be at least 5m ahead of the working face and its left and right sides shall not be less than 4m from the roadway. Its scope shall be increased with the burst hazard level of coal seam.

The working principle of the safety barrier zone is illustrated. This zone is formed by a pattern of advance boreholes and intended to eliminate local burst hazard in coal seam and isolate burst momentum outside the boundary.

Determining whether burst hazards within the movable safety barrier are totally eliminated depends on multi-parameter prediction means and the accuracy must be above 95%. If burst hazards are eliminated and the presence or absence of burst hazards can be accurately determined, then the complex coal uncovering technique becomes very simple, and the coal seam can be uncovered and crossed just by conventional driving method.

3.4. Coal uncovering method
Under the protection of the safety barrier which eliminates burst hazards around the working face, gradual advancement in multiple rounds involving small amounts of explosives for blasting is made to avoid activating burst-prone coal seam and avoid the use of shock blasting. In this way the working face is advanced normally into coal mass. The whole coal uncovering process generally lasts 7-25 days.

Gradual advancement shall employ smooth blasting to provide neat surfaces and uniformly distributed pressure around the roadway. The amount of explosive used is 1.3~2.0kg/m³. Most cross sections of the tunnel are larger than 100m². A drift may be blasted and excavated before enlarging it to the whole cross section.

4. Application of Gradual and Fast Coal Uncovering Technique
Huayan Tunnel is a vital passageway connecting the east and west sides of Zhongliangshan and located between Zhongliangshan and Huafu tunnels of Chengdu-Chongqing Expressway in the city of Chongqing. It is about 4,970m long. Its site area is in lower Guanyinxia anticline in eastern Sichuan sunken fold belt and passes through Quaternary, Jurassic, Triassic and Permian strata. Along the anticline axis is developed Zhongliangshan fracture zone. The coal-bearing strata of Permian Longtan Formation are in a mined area of a mine south of Zhongliangshan, and minable seams face coal and gas
burst hazards. Therefore, this tunnel faces coal and gas burst risks in addition to crossing solid coal, mined-out area and complex geological structures.

The Permian Longtan Formation strata to be crossed by the tunnel contain 10 coal seams totaling 14.9m in thickness, including 9 minable and locally minable seams (K₁, K₂, K₃, K₄, K₅, K₇, K₈, K₉ and K₁₀). Zhongliangshan mine area is a typical coal and gas burst prone mine in China. Zhongliangshan South Mine data show that coal seam K₉ and K₁₀ south of 3# south crosscut on the west wing of the mine and south of 2# south crosscut on the east wing are combined to a thickness of 5m on average. The mine area contains coal bed gas of up to 2.15~4.7MPa pressure and up to 15.8~19.3m³/t content, and is therefore at risk of burst. Minable coal seams in the Zhongliangshan South Mine + 280m above it to be crossed by the tunnel has long been mined and contains mined-out area and solid coal.

As the tunnel advances, advance probing suggests a 5m thick solid coal seam at ZK3+200 of left track, without obvious tectonic structure and other abnormal geology. Further comparative analysis of geological and mining data on Zhongliangshan South Mine shows coal seam K₉ and K₁₀ south of 3# south crosscut on the west wing of the mine and south of 2# south crosscut on the east wing are combined to a thickness of 5m. Based on this analysis, the 5m thick coal seam detected at ZK3+200 should be the combined K₉ and K₁₀ seam.

In order to verify suitability and reliability of the study result, area and working face burst hazards are predicted at 14m, 5m, 3m and 2m normal distance by collecting coal samples from drilled holes for determination of coal bed gas content $W$ and cutting gas desorption indicator $K₁$. Boreholes are arranged as shown in Fig. 2; determination results are presented in Table 1.

![Fig. 2 Schematic section of prediction hole arrangement](image)

### Table 1 Prediction result of coal seam burst hazard

| Bore hole No. | Normal distance 14m | Normal distance 5m | Normal distance 3m | Normal distance 2m |
|--------------|---------------------|-------------------|-------------------|-------------------|
|              | $W$   | $K₁$   | $W$   | $K₁$   | $W$   | $K₁$   | $W$   |
| 1            | 6.80  | 0.38   | 6.75  | 0.20   | 5.30  | 0.26   | 5.26  |
| 2            | 5.30  | 0.27   | 5.19  | 0.21   | 5.17  | 0.29   | 5.38  |
| 3            | 6.39  | 0.28   | 5.37  | 0.35   | 6.02  | 0.11   | 4.96  |
| 4            | 5.73  | 0.23   | 3.94  | 0.15   | 4.12  | 0.15   | 5.88  |
| 5            | 4.66  | 0.16   | 4.21  | 0.17   | 4.69  | 0.09   | 4.23  |

The measurement results show neither area prediction indicator nor working face burst hazard prediction indicator has exceeded critical value, and drilling has not encountered burst, jamming or jacking. After the coal seam is determined to be free of burst hazard, it is safely and smoothly uncovered under safety protection measures.
The practical application of burst hazard prediction indicators established through this study demonstrates using gas content $W$, and area prediction and cutting gas desorption indicator $K_f$ for working face prediction is suitable, reliable and correct as an effective guide for tunnel coal uncovering.

5. Conclusions
(1) The five-step gradual and fast coal uncovering technique for gassy tunnels based on reliable prediction and inspection features gradual, steady uncovering of coal seam in steps. Use of this technique can improve coal uncovering efficiency and assure safety in tunnel coal uncovering.

(2) Application of this technique to Huayan Tunnel demonstrates using gas content $W$, and area prediction and cutting gas desorption indicator $K_f$ for working face prediction is suitable, reliable and correct as an effective guide for tunnel coal uncovering.

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