Study on Prediction of Gas Burst Hazard Before Advancing a Tunnel Through Coal Seam

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Abstract: This paper discusses how to predict burst hazard when advancing a tunnel through a gassy coal seam in order to prevent gas burst disaster during tunnel excavation. It covers prediction of burst hazard for Huayan Tunnel of Chengdu-Chongqing Expressway in the city of Chongqing before its left tube is advanced through a gassy coal seam at ZK3+200. The prediction result is reliable and has ensured the safety and stability of the Huayan Tunnel while it is advanced through the gassy coal seam.

1. Introduction
Mountains and hills make up about 75% of China's land. In transport infrastructure development the quantities of tunneling work are very large especially in the southwestern region including Chongqing, Sichuan and Guizhou. When a tunnel passes through gassy coal measure strata, coal gas in the strata will be desorbed and enter the tunnel opening. Such a tunnel is called gassy tunnel. In addition to construction risks faced by general tunnels, a gassy tunnel also faces the risk of gas disasters most notably gas burst incident.

The key of safe advance through a gassy coal seam lies in accurate prediction of burst hazard in the coal seam ahead and putting in place appropriate preventive measures prior to advance through the gassy coal seam. In response, this paper will discuss how to predict burst hazard before a tunnel is advanced through a gassy coal seam by performing burst hazard prediction before Huayan Tunnel of Chengdu-Chongqing Expressway in the city of Chongqing is advanced through a gassy coal seam.

2. Project Overview
Huayan Tunnel in Chongqing is a vital passageway connecting the east and west sides of Mount Zhongliang and a Class I urban artery. It is a two-way tunnel with two tubes, each accommodating 3 lanes. The left tube is 4964m long and the right one 4972m long. There are abundant coal resources in the tunnel site area where coal seams K1, K2, K3, K4, K5, K6, K7, K8, K9 and K10 in upper Permian Longtan Formation are located. These coal seams were mined as part of South Zhongliangshan Mine. Each coal seam contains a high content of gas at high pressure with the potential for burst. According to design scheme Huayan Tunnel will pass through coal pillars and mined-out areas left in South Zhongliangshan Mine and up to 20 coal seams due to the anticline
structure effect at Mount Zhongliang. Coal and gas bursts coupled with mined-out areas make construction of the tunnel extremely risky.

3. Prediction Technology for Gas Burst Hazard Before Advancing a Tunnel Through Coal Seam

3.1. Determining prediction distance

If gas pressure test holes are drilled in the tunnel face at a normal distance of 5m from the coal seam, this distance (normal distance) might be too small because excavation-induced stress changes will cause plastic deformations of surrounding ground and propagation of fissures and make it ineffective to seal the holes according to gas pressure measurements and hence impossible to accurately measure the true gas pressure in the coal seam. Therefore, study is required to determine a reasonable prediction distance to obtain burst prediction indicators for a large size tunnel.

During tunnel excavation the surrounding ground deforms and moves into the tunnel opening under the ground stress effect and redistribution of the stresses in the ground ahead of the tunnel face occurs. A stress concentration zone appears somewhere ahead of the face. Due to swelling of and stress relief in the ground near the face, a relaxation zone is formed. The zone outside the stress concentration zone and far from the face is original stress zone because it is not influenced by tunnel excavation. As the tunnel is advanced, the coal seam will enter the original stress zone, stress concentration zone and relaxation zone sequentially ahead of the tunnel until being penetrated by the tunnel. Prediction of burst hazard associated with the tunnel passing through the solid coal zone shall take place before the coal seam enters the stress concentration zone.

Consequently, we can determine the reasonable prediction distance, L, by analyzing stress field changes in the coal seam during tunnel advancement using numerical simulation software such as Flac$^3$D and 3DEC.

3.2. Determining the prediction hole control scope

To ensure accurate prediction of burst hazard associated with advancing a tunnel through coal seam, the prediction holes must be located within some distance to and beyond the envelope. Too small a control scope will result in inaccurate and unreliable prediction of actual gas occurrence state in the coal seam to be penetrated. Therefore, the prediction holes control scope shall be defined for a large size tunnel.

Following tunnel excavation, three zones, i.e. relaxation zone, stress concentration zone and original stress zone exist ahead of the tunnel face. This is also the case in every direction around the excavated opening. As shown in Fig. 1, stress disturbance zones induced by excavation exist around the tunnel. Stresses in coal masses inside the disturbance zone are redistributed such that stresses near the excavated opening decrease leading to coal mass yield failure and low resistance to deformation. Stresses in coal mass beyond the relaxation zone increase with high stress gradient and have huge potential for elasticity. Both coal mass stress and gas occurrence state beyond the stress disturbance zone remain in the original state and almost under no influence of tunnel excavation [6-7].
In order to accurately measure the actual gas occurrence parameters in the coal seam ahead of the tunnel, prediction holes shall at least be arranged within some distance around and ahead of the envelope, i.e. \( K_{\text{above}} \), \( K_{\text{below}} \), \( K_{\text{left}} \) and \( K_{\text{right}} \) given in Fig. 1.

Similarly, we can determine the prediction hole control scope by analyzing stress field distribution in coal mass around the envelope using numerical simulation software such as Flac 3D and 3DEC.

3.3. Number and arrangement of prediction holes
We determine the arrangement of burst hazard prediction holes before the tunnel is advanced through solid coal zone based on the determined prediction distance and prediction hole control scope.

Prediction holes shall be made within the prediction distance. To fully control the coal uncovering region, at least 5 prediction holes shall be drilled into the coal seam above, below, left, right and right ahead of the tunnel cross section for coal uncovering. At least 1 hole shall reach original stress zone. If the geological conditions are complex, the number of prediction holes shall be increased as appropriate to ensure prediction results are reliable and accurate.

3.4. Determining prediction indicators
In predicting burst hazard in coal seam under such complex conditions as advancing tunnel through coal seam, use of gas pressure as prediction indicator will result in low measurements. Meanwhile, because forming a closed environment is hard due to the presence of fissures in the surrounding ground the success rate of gas pressure measurement will be very low.

Currently, extensive applications of gas content as an indicator in measurement of basic gas parameters, prediction and assessment of coal and gas burst hazards in the coal mining industry have produced remarkable results mainly because these measurements are more close to original values, simpler and take less time. Relative to gas pressure indicator, the gas content indicator has such advantages as flexible arrangement of measuring points, no limit by geological conditions, simple process and high success rate.

Therefore, the gas content indicator is selected for burst prediction before advancing a tunnel through the coal seam: a. if gas content \( W < 8 \text{m}^3/\text{t} \), there is no burst hazard; b. if gas content \( W \geq 8 \text{m}^3/\text{t} \), there is burst hazard; c. if gas dynamics such as burst, jamming, jacking and sound due to sudden pressure release occur in prediction holes, the presence of burst hazard is clear.

4. Field Application of Burst Hazard Prediction Technology
During tunnel construction, advance probing found a 5m thick solid coal seam at ZK3+200 of the left tube. Based on analyses of geological and mining data on South Zhongliangshan Mine, this seam is determined to be the combined \( K_9 \) and \( K_{10} \) seam. Safe construction of the tunnel requires prediction of the burst hazard associated with advancing the tunnel through this coal seam.

(1) Determining prediction distance
Using Flac\textsuperscript{3D} we numerically modeled stress field changes in the coal seam during tunnel excavation and found stress values at monitoring points in the coal seam began to change when the tunnel envelope was at a horizontal distance of 16m from the coal seam. Therefore, the boundary of stress concentration zone is at the place 16m in horizontal distance from the coal seam. Based on the dip angle of the coal seam, the reasonable burst hazard prediction distance $L$ can be calculated as 14m.

(2) Determining the prediction hole control scope

Analyses of the distribution of stress field in coal mass around the envelope suggest tunnel excavation disturbs stresses in the surrounding ground in both horizontal and vertical directions. The range of stress disturbance zone in vertical direction is $-10m\leq z\leq 20m$ while upper and lower tunnel envelopes are $z_{\text{above}}=8m$ and $z_{\text{below}}=-2m$ respectively. Therefore, the prediction hole control scope in vertical direction, $K_{\text{above}}$, shall at least be 12m and $K_{\text{below}}$ at least be 8m. The range of stress disturbance zone in horizontal direction is $-15m\leq x\leq 15m$ while the left and right envelopes are $x_{\text{left}}=8m$ and $x_{\text{right}}=8m$ respectively [8]. Therefore, the prediction hole control scope in horizontal direction, $K_{\text{left}}$ and $K_{\text{right}}$, shall at least be 7m. Thus the value of $K$, the prediction hole control scope for advancing the tunnel through solid coal, is calculated as shown in Table 1.

| Hole control scope (m) | $K_{\text{above}}$ | $K_{\text{below}}$ | $K_{\text{left}}$ | $K_{\text{right}}$ |
|-----------------------|---------------------|---------------------|---------------------|---------------------|
|                       | 12                  | 8                   | 7                   | 7                   |

(3) Determining the number and arrangement of prediction holes

Prediction holes shall be drilled before the tunnel approaches the point 14m in normal distance ahead of the coal seam. To fully control the coal uncovering region, at least 5 prediction holes shall be drilled into the coal seam above, below, left, right and right ahead of the tunnel cross section for coal uncovering. At least 1 hole shall reach original stress zone (12m in vertical distance above the envelope, 8m in vertical distance below the envelope and 7m in horizontal distance on the left and right sides). The arrangement of prediction holes is illustrated in Fig. 2.

![Fig. 2 Schematic arrangement of burst hazard prediction holes for advancing the tunnel through coal seam (reverse direction)](image)

(4) Measuring prediction indicator and drawing prediction conclusion

The measured gas content $W$ is 5.73-6.80 m$^3$/t, less than the critical value of 8 m$^3$/t and close to the gas content of 6.07m$^3$/t in coal seam K3 of South Zhongliangshan Mine as measured at the elevation of the tunnel. The value of $W$ is relatively accurate and can reflect accurately and reliably the burst hazard posed by the coal seam. To ensure the accuracy of prediction result, we also measured cutting gas desorption indicator $K_1$ at 0.11-0.38 ml/g$^{*}$min$^{1/2}$. This value is less than the critical value of 0.5 ml/g$^{*}$min$^{1/2}$ [9-10].
The measurement results show none of the burst hazard prediction indicators including gas content and cutting gas desorption 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.

5. Conclusions
(1) We have proposed the technology to predict burst hazard associated with advancing a tunnel through gassy coal seams, including determining prediction distance, prediction hole control scope, the number and arrangement of prediction holes, selecting and measuring burst prediction indicator, and drawing prediction results.
(2) We have predicted the burst hazard associated with the left tube of Huayan Tunnel passing through a gassy coal seam at ZK3+200 and found none of the burst hazard prediction indicators including gas content and cutting gas desorption indicator exceeded critical value. Thus it is determined that there is no burst hazard.

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