In situ stress test device applied to boreholes with a small aperture and stress field inversion technique in coal mines

N B Zhang¹,², S K Zhao² and Z G Deng²

¹ School of Mechanics and Civil Engineering, China University of Ming and Technology, Beijing 100083, China.
² Mine Safety Technology Branch, China Coal Research Institute, Beijing 100013, China

Abstract. In situ stress has an important influence on the failure of rock in coal mines, but how to well utilize the test result of in situ stress to guide the engineering is still unclear. The stress to induce coal bursts was analyzed in this study. Based on the test principle of hydraulic fracturing, a quick-test device used in boreholes with an aperture of 31 mm was developed to measure the in situ stress. An inversion software was programmed based on the multiple linear regression method to obtain the stress field. Lastly, three engineering cases were presented to introduce the application of the new technique, combining the in situ stress test and stress field inversion. The results show that the new method introduced in this paper is applicable for the evaluation of bursting risk, layout optimization of pre-mining, and mechanism analysis of coal bursts. It has a great significance for the safety of coal mines.

Keywords. In situ stress test, small aperture, stress field inversion, coal bursts

1. Introduction

In situ stress is essential for underground engineering. For many years, devices and methods of in situ stress measurement have been investigated [1-3]. In coal mines, stress relief testing is one of the most widely used methods [4,5]. However, it is found that there are some shortages, including the long testing period and low success rate when the stress relief testing is used in the relatively weak rock of coal mines [6]. To improve the applicability of the in situ stress measurement in coal mines, Hongpu Kang developed a hydraulic fracturing device that is suitable for boreholes with an aperture of 56 mm. It was also applied successfully in many coal mines in China [7]. However, the aperture of testing boreholes is still too big for a cramped room in coal mines. Thus, it is necessary to create a device applicable for boreholes with a small aperture for the in situ stress test.

According to test results of the in situ stress, the data obtained from the practical site are discrete and only consist of a few measurement points. However, the engineering needs to learn the distribution of the stress field. Hence, merely getting several in situ stress data is not enough [8]. Based on the results of in situ stress measurement, a couple of inversion methods were developed, but how to use them in engineering is still under debate [9-11].

In this article, an in situ stress testing device was developed for boreholes with an aperture of 31 mm. In addition, a three-dimensional (3D) stress field inversion software was programmed based on the method of the multiple linear regression analysis. With the two techniques mentioned above, three cases were introduced to present their application in engineering.

2. Stress analysis of coal bursts

The stress distribution is closely related to the failure of rock. For decades, the quantity of coal bursts surges with the coal mines going deep in China mainly due to the high in situ stress [12]. Based on the
various mechanism [13,14], stress, such as in situ stress, mining-induced stress, gas pressure, and water pore pressure, among others, is involved in the rock failure. In recent years, people are more and more aware that the stress of rock is the core factor for the disaster’s occurrence [15].

Based on engineering cases of coal bursts and laboratory experiments, Qi [16] proposed the theory named “three factors of coal burst.” He found that stress, structure, and bursting tendency are the major factors for coal bursts. In addition, he realized that changing the stress in coal can prevent coal bursts [17]. From our point of view, rock stress is the most essential factor to induce a coal burst. There are two types of coal bursts in engineering cases: (1) Coal bursts often occur in roadways under high in situ stress. Near the bursting site, structures such as faults often don’t exist. This kind of coal burst is induced probably only because the stress of coal exceeds its strength. (2) Coal bursts often occur in the non-bursting liability coalbed which possesses a low uniaxial compressive strength. Therefore, the critical principle of coal bursts should be given as

$$\sigma_d \geq \sigma_c$$  \hspace{1cm} (1)

where $\sigma_d$ is the ultimate stress of coal in bursting risk zones and $\sigma_c$ is the critical stress of coal for bursting.

Although structures are not essential for coal bump, they can create the additional stress $\sigma_a$. Equation (1) can then be written as

$$\sigma_r + \sigma_a \geq \sigma_c$$  \hspace{1cm} (2)

where $\sigma_r$ is the gravity stress of rock over the coalbed and $\sigma_a$ is the additional stress caused by mining or geological structures. Furthermore, Equation (2) can be written as

$$\sigma_r + \sigma_m + \sigma_g \geq \sigma_c$$  \hspace{1cm} (3)

where $\sigma_m$ is the additional stress due to mining, for example, improper pillars, unfavorable roadway, and adjacent gobs, among others; $\sigma_g$ is the additional stress caused by geological structures such as faults, phase transformation, folds, and so on; and $\sigma_m$ will increase if structures get more complex or it is disturbed by dynamic stress like hard roof fracturing [18,19].

Dou [20] argued that coal with strong bursting liability presents lower critical stress. Furthermore, the mining or geological activities create more cracks in the coal, which also can lower its critical stress.

From the analysis above, structures and bursting liability can increase the bursting risk through making additional stress or lowering the critical stress. Therefore, stress is the core factor of coal burst. Hereby, we focus on the stress to promote solving engineering issues.

3. In situ stress test in boreholes with a small aperture: principle and device

3.1. Principle of the in situ stress testing

The hydraulic fracturing method is employed to develop the device. Three hypotheses are as follows: (1) Rocks are linearly elastic and isotropic. (2) The rock is intact, and the fluid to fracture the rock is non-permeable. (3) One of the principal stress components is parallel to the centerline of boreholes. Figure 1 shows the simplified plane stress model based on elastic mechanics and hypotheses above.

Based on the mechanics analysis in Appendix, the in situ stress is given by Equations (4), (5), and (6):

$$\sigma_H = 3P_s - P_t - P_0$$  \hspace{1cm} (4)

$$\sigma_h = P_s$$  \hspace{1cm} (5)

$$\sigma_v = \rho gd$$  \hspace{1cm} (6)

where $\sigma_H$ is the maximal principal stress, $\sigma_h$ is the minor principal stress, $\sigma_v$ is the vertical stress, $P_s$ is the closed pressure, $P_t$ is refracturing pressure, $P_0$ is the pore pressure, $\sigma_v$ is the vertical stress, $\rho$ is the average rock density, $g$ is the gravity acceleration, and $d$ is the depth.
3.2. In situ stress test device applied to boreholes with the small aperture

Based on the principle of stress measurement by using the hydraulic fracturing method, a kind of in situ stress test device was developed. This device was especially used for boreholes with a small aperture. Figure 2 shows the components of the test equipment.

The test steps are as follows: (1) A pair of inflatable packers are plugged into the borehole to seal off a specific section. (2) The fluid in the test section can then be pressurized, and the pressure over time must be recorded by a digital recorder. (3) From the record curves of pressure, the characteristic pressure parameters can be obtained. (4) According to the calculation formula, the results, including the tensile strength of the rock and the maximal and minor principal stress at the observation point, can be acquired. Table 1 presents the comparison of the results between the new and traditional devices in the same coal mine. As presented in Table 1, the $\sigma_{th}$ orientation of two results is very close, and $\sigma_{th}/\sigma_{hb}$ decreases as the test depth increases, which is consistent with the variation rule of in situ stress worldwide. Thus, the new device is reliable for an in situ stress test in coal mines.

**Table 1.** Comparison between two test results of in situ stress measurement devices.

| Test device | Point number | Depth/m | $\sigma_{th}$/MPa | $\sigma_{hb}$/MPa | $\sigma_{th}/\sigma_{hb}$ | Orientation of $\sigma_{th}$ |
|-------------|--------------|----------|-------------------|------------------|-------------------------|--------------------------|
| Traditional | 1            | 427      | 12.08             | 7.20             | 1.68                    | N37.2°W                  |
|             | 2            | 528      | 16.22             | 8.51             | 1.91                    | N22°W                    |
| New         | 1            | 746      | 20.92             | 14.64            | 1.43                    | N37°W                    |
|             | 2            | 780      | 21.86             | 14.76            | 1.48                    | N24°W                    |

Compared with the traditional methods such as the stress relief method, the diameter of boreholes used for the new device decreases from 130 mm to 31 mm. Thus, there is no need to use a heavy
drilling machine for a big borehole. Moreover, the space drilling activities need is also small, which is adaptable to the cramped working room in coal mines. Due to the efficient borehole drilling and sample test procedure, the test period falls off from 4 weeks to 3 days. In addition, it is suitable for soft sedimentary rock such as mudstone or shale in coal mines since coring is not needed.

4. Inversion technique of 3D stress field in coal mines

4.1. The inversion principle

The stress field is influenced by many factors such as topography, stratum, structures, water, and temperature, among others. Although it is difficult to get the accurate value of stress, the distribution and evolution of the stress field can be obtained through linear and nonlinear methods, which are very useful to engineering. Among them, the multiple linear regression analysis is a relatively mature linear inversion method. It is applicable for sedimentary rock which is shallow and with a relatively simple structure compared with deep rock. The procedure of the inversion method is as follows: At first, the elaborate 3D numerical model is constructed based on the detailed geological data of coal mines. The “calculated stress value” affected by each factor is then obtained via numerical computation. By regression analysis method, the “calculated stress value” needs to approach the “measured stress value” that is tested by the new device. Lastly, the in situ stress field can be calculated using the regression Equation (7).

$$\sigma_{fp} = \sum_{i=1}^{n} L_i \sigma_{ijp}^i$$

where $m$ is the number of in situ stress test points, $n$ is the number of factors, $j$ is a certain stress component, $k$ is a certain testing point, $L$ is the regression coefficient, and $\sigma^*$ is the component of the in situ stress test.

Each in situ stress component at the test point can be acquired using Equation (8):

$$\sum_{i=1}^{n} L_i \sigma_{ijp}^i = \sigma_{ijp}^*$$

4.2. Software of the 3D stress field inversion

Based on the multiple linear regression analysis, a 3D in situ stress field inversion software named AAGS-2.0 was developed. Figure 3a and 3b shows the flowchart of the inversion procedure and the structure of the software, respectively. Firstly, the numerical models, including geometric models and grid models, are created, relying on the geological data. The in situ stress data tested by the new test device are then inputted into the software. The parameters of the boundary condition are confirmed through the inversion method. Meanwhile, the mining condition can also be involved in the analysis. By multiple correlation coefficient $\gamma$, among others, the inversion result is tested. If the multiple correlation coefficient $\gamma$ can be accepted, then the stress field is outputted. If not, one must go back to adjust the parameters of the boundary condition. The result still needs to be tested by engineering. If the result is consistent with the phenomenon of the physical field, then the stress field is accepted. If not, one must repeat to adjust the boundary condition parameters until a reasonable result is obtained. After obtaining the favorable stress field, post-processing, including different stress contours, isograms, and cross section views, can be done by the software.
5. Engineering cases

Hereby, by 3D stress field inversion based on the in situ stress test, three cases were applied for coal burst prevention. The cases are about the assessment of coal burst risk, the optimization of premining layout, and the dynamic analysis of coal burst, respectively.

5.1. Assessment of the coal burst risk

The Jixian Coal Mine is a coal burst mine located in Heilongjiang Province, China. Figure 4a shows the numerical model based on geological data of the Jixian Coal Mine. The stress distribution of the mining stope named left one was obtained by 3D in situ stress field inversion software, revealing that three zones with a high risk of coal burst are located in the tailentry, as is shown in Figure 4b. During mining, the coal and rock failure occurred in the three regions, which was consistent with the evaluation results.

Figure 4. Coal bump risk evaluation of left one stope in the Jixian Coal Mine. (a) The whole numerical model. (b) The vertical stress distribution of a stope before mining

5.2. Optimization of the premining layout

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Firstly, two types of design schemes for mining No. 16 coalbed were considered in the Jixian Coal Mine to avoid the influence of coal pillars subjected to No. 9 coalbed. One design is two wing (see blue lines in Figure 5a) and another is roadway interlaced (see blue lines in Figure 5b). To compare two schemes in terms of the coal burst risk, the stress field was obtained by the inversion technique, as is shown in Figure 5. The stopes and roadways need to pass through several stress concentration areas underlying coal pillars in the two-wing design (see Figure 5a). In the roadway-interlaced solution, the high-stress areas are located in the middle of stopes, and two drifts are in low-stress zones (see Figure 5b). Thus, the two-wing design is inferior to the roadway-interlaced one, which was accepted by the Jixian Coal Mine to prevent coal bumps.

![Figure 5](image.png)

**Figure 5.** Stress distribution of coal No. 16 in the Jixian Coal Mine under two mining layouts. (a) Two wing. (b) Roadway interlaced

5.3. Dynamic analysis of a coal burst

A tunnel located in Guizhou Province, China, needs to pass through a mountain containing multiple sets of coal seams. Guizhou Province is an earthquake-prone terrain. The tunnel can easily be affected by earthquakes during excavating. Figure 6 shows the numerical model of the tunnel created by the 3D stress field inversion software. To assess the risk of rock failure due to earthquakes, stress waves were loaded into the model.

![Figure 6](image.png)

**Figure 6.** Numerical model of the tunnel. (a) Whole model. (b) Relative position of coal seam and tunnels

Figure 7 shows the stress distribution of the tunnel. The stress of the floor where the pilot tunnel encounters the coal seam approaches 9.12 MP before the dynamic loading (see Figure 7a). While stress waves were loaded, the vertical stress sharply increases to 11.2 MPa (see Figure 7b). During the tunnel advancing, floor bump and gas outburst occurred at the high-stress zone because of the occurrence of three earthquakes with the magnitude of 3.0~3.4 near the tunnel. Particularly, one earthquake’s hypocenter was 2-km deep, 160-km away, and about 7 h before the burst event.
Figure 7. Vertical stress distribution of model before and after stress waves. It shows the stress contour at the XZ plane along the centerline of the pilot tunnel. (a) Before the dynamic loading. (b) After the dynamic loading.

6. Conclusion and outlook

6.1. Conclusion
1) Stress is the most crucial factor that induces coal burst. By creating additional stress or lowering the critical stress, structures and bursting liability can affect the risk of coal bursts.
   2) Based on the hydraulic fracturing principle, the in situ stress test device was developed for boreholes with a small aperture. It has a much good application for coal mines with a narrow operation space and weak sedimentary strata.
   3) The stress field can be obtained by the 3D stress field inversion software, which is developed based on the multiple linear regression analysis.
   4) The technique of 3D stress field inversion based on in situ stress tests is applied successfully in the coal burst risk assessment, optimization of premining layout, and dynamic analysis.

6.2. Outlook
In the future, the in situ stress test device for boreholes with a small aperture should be investigated to improve the test convenience and accuracy. Moreover, we realize that the accuracy of stress field inversion is rough owing to the linear regression method. Further research is indispensable to improve the inversion precision. Moreover, dynamic real-time inversion and intelligent inversion need to be developed. Lastly, the application of stress tests and inversion techniques should be promoted to predict coal bursts more accurately and efficiently.

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Appendix
By the stress analysis at point M outside the circular hole (see Figure 1), we can identify the stress of point A from Equation A.1:

\[ \sigma_A = \sigma_{A'} = 3\sigma_2 - \sigma_3 \]  \hspace{1cm} (A.1)

The correspondence between hydraulic pressure and stress field is given by

\[ P_b = 3\sigma_2 - \sigma_1 + T_{hf} - P_0 = 3\sigma_h - \sigma_H + T_{hf} - P_0 \]  \hspace{1cm} (A.2)

\[ P_i = 3\sigma_h - \sigma_H - P_0 \]  \hspace{1cm} (A.3)

where \( P_b \) is the first fracturing pressure, \( P_0 \) is the pore pressure, \( T_{hf} \) is the tensile strength, \( \sigma_H \) is the maximum principal stress, and \( \sigma_h \) is the minimum principal stress.

Equations (4), (5), and (6) can then be derived from Equations (A.2) and (A.3).

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