



In-situ stress measurements and stress distribution characteristics in underground coal mines in China

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ABSTRACT

The theory, equipment and method of hydraulic fracturing stress measurement used in underground coal mine roadways in China are presented. A quality assurance system and a quality ranking scheme were developed for hydraulic fracturing stress measurements under specific conditions encountered in Chinese underground coal mines. During the last 8 years, a total of 204 hydraulic fracturing stress measurement campaigns have been carried out in 49 coal mines within 13 Chinese coal districts. The test sites which are located in sub-horizontal, inclined and steeply dipping coal measures range in depth from 69.2 m to 1283 m. Each stress data record was assigned a quality between A and E according to a proposed data quality ranking scheme. A total of 97 stress data records of A and B quality were used to investigate the distribution characteristics of in-situ stresses within the coal districts. Generally, in-situ stresses increase with depth. In shallow coal mines, the rate of increase in horizontal stresses with depth is greater than the rate of increase of vertical stress. With increasing depth the rate of increase in horizontal stresses decreases. A considerable scatter in the in-situ stress test data may be due to distinct differences in both the strength and deformation moduli of strata located in varying geological environments and different coal districts. In addition, large folds and faults often result in a change in orientation of the maximum horizontal stress, and in distinct changes in stress values. Three types of stress field distribution have been noted with $\sigma_H > \sigma_h > \sigma_v$ found mainly in relatively shallow coal mines (<400 m), the $\sigma_H > \sigma_v > \sigma_h$ type in moderately deep coal mines (400–600 m), and the $\sigma_v > \sigma_H > \sigma_h$ type predominantly in moderately deep to deep coal mines. The ratio of the maximum horizontal principal stresses to vertical stress is usually between 0.5 and 2.0 in the coal districts.

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1. Introduction

In China, coal seams are usually extracted by underground mining methods. A great number of roadways and other underground openings are required to be excavated and supported. According to an incomplete statistical record, more than 10,000 km of roadways are excavated each year in China with 80% of these in coal seams. Constructing such a large number of underground structures is very seldom undertaken in other industries. The stability of these roadways is an essential component of Chinese coal mining production.

The stability of roadways depends mainly on rock stress, rock strength, geological structures and their interaction. Rock stress is the driving force causing both deformation and failure of the coal-rock mass surrounding the roadways. For coal mining, especially longwall mining, the stresses in the surrounding rock are the superposition of in-situ, mining-induced and supporting stresses. In-situ stresses are the most basic and critical component.

The main controls on in-situ stresses are gravitational and tectonic forces, particularly associated with horizontal tectonic movements which play an important part in the formation and characteristics of in-situ stresses. While the gravitational stress field due to the overlying rock mass is relatively simple, the factors generating the tectonic stress field are more complicated. The distribution of the tectonic stress field is extremely irregular and constantly changing with time; consequently it is impossible to apply precise analytical solutions to describe the tectonic stress field. An efficient way to investigate the in-situ stress field is to carry out a number of stress measurements, analyze the results and find out the statistical distribution and patterns of variation.

In Chinese coal mines, the geological environments of coal seams are complex, and influenced by numerous types of geological structure such as faults, folds and collapse features. The in-situ stress fields found in Chinese coal districts are complex and inconsistent resulting in significant variations in mining conditions. For example, the mining depth in some coal districts in Western China is in the order of tens of meters, while in Eastern China, it can reach up to 1400 m. The depth of mine operations and the in-situ stress distribution control the ground deformation and failure mechanisms

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in the near field rock mass surrounding the openings within the various coal districts. In addition, accidents in coal mines, such as roof collapse, coal and gas outburst, rock burst, mine seismicity and water inrush, are closely related to in-situ stresses. In deep underground coal mines in particular, the occurrence of a series of important mine failures has been associated with high in-situ stresses and stress redistribution due to extensive mining. The development of improved underground mining designs based on in-situ stress data, including roadway layout and support, working sequences and technologies, can effectively reduce the number of the accidents in Chinese coal mines. In-situ stress measurements and analyses of their spatial distribution are therefore very important factors in ensuring improved safety and production.

Numerous methods exist for in-situ stress measurement including mechanical, geophysical and geological methods (Amadei and Stephansson, 1997; Ljunggren et al., 2003; Chistiansson, 2006). The physics of stress measurements allow subdivision into six methodologies, i.e., mechanical, strain gauge, diffraction, ultrasonic and micromagnetic methods (Zang and Stephansson, 2010). Two of these methods, hydraulic fracturing and borehole relief, have been widely utilized in field stress measurements. Hydraulic fracturing is suitable for stress measurements in deep boreholes and can be classified into traditional hydraulic fracturing (HF) and hydraulic testing of pre-existing fractures (HTPF) (Haimson and Cornet, 2003). The measurement principles used in traditional hydraulic fracturing were first presented by Hubbert and Willis in 1957 (Hubbert and Willis, 1957), and then further developed by others (Baumgärtner and Zoback, 1989; Bjarnason et al., 1988; Ito et al., 1999). For stress measurements carried out in deep boreholes, a combination of hydraulic fracturing and other methods including borehole breakouts, drilling-induced tensile fractures and slip on faults, can result in improved accuracy and reliability (Lund and Zoback, 1999; Zoback et al., 2003). In China, the hydraulic fracturing method has also been extensively studied and developed (Li et al., 1983; Li, 1989). Stress measurement campaigns were carried out by borehole relief and hydraulic fracturing methods, and the local stress distribution characteristics presented (Li et al., 1983; Cai et al., 2000). In Hong Kong, a total of 149 tests were carried out in 18 boreholes and the relationship between principal stress ratio and depth presented (Klee et al., 1999).

The stress data derived from these different methods can not only be used to investigate local stress distribution characteristics, but also to study lithospheric stress distribution and its changing trend around the world. The World Stress Map (WSM) project is a research project commenced in 1986 with the aim of founding an open-access database of present-day stress fields of the global crust. This project has been continued and further developed. The data records of the WSM in 1992 were mainly from focal mechanism solutions, volcanic alignments and fault slip interpretations (Zoback, 1992). Only less than 5% of the data records were derived from hydraulic fracturing and borehole relief methods. The current WSM database released in 2008 consists of 21,750 data records (Heidbach et al., 2008, 2009). Almost 17,000 of these data records are of high quality. These data records are derived from focal mechanisms, borehole breakouts, drill-induced fractures, fault slip, hydrofracturing, overcoring, volcanic alignment and petal centreline fractures etc. Only 1.9% of the records are derived from hydrofracturing and overcoring. Based on the WSM database release of 2008, Heidbach, et al. investigated the global crustal stress pattern (Heidbach et al., 2009b).

In most of the underground coal mines in China the overcoring method is applied to measure in-situ stresses with hydraulic fracturing being used in very few mines. Due to the special working conditions in Chinese underground coal mines, such as methane problems and damp and narrow working spaces, stringent requirements are required for both the technical specifications and reliability of measuring instruments and equipment. Most instruments and

equipment applied in other mines and underground works cannot be directly used in underground coal mines. As a result of a lack of instruments and equipment suitable for underground coal mines, many coal mines in China have not conducted stress measurement campaigns. Without in-situ stress data, it is difficult to reasonably and reliably design the roadway support patterns. To provide a solution to this problem, the Mining and Designing Branch of the China Coal Research Institute has developed a full set of in-situ stress measurement equipment which includes a small diameter hydraulic fracturing rig that can be easily used in underground coal mines (Kang and Lin, 2007; Kang et al., 2009). During the last 8 years, this equipment has been utilized in many coal districts in China, and a great amount of stress data has been collected. The stress data has been applied in roadway support designs in many coal districts. In this study, the principle of the hydraulic fracturing method is first illustrated and then the results of in-situ stress measurements carried out at 204 test sites in Chinese coal mines are presented and discussed.

2. Principles and methods of hydraulic fracturing stress measurements in underground coal mines

Hydraulic fracturing stress measurement can be conducted either from the ground surface or in roadways. For stress measurement from the ground surface, a vertical borehole is drilled from the ground, and a section is sealed off with a straddle packer. The sealed-off section is then slowly pressurized with water until the borehole wall is ruptured through tensile failure and a hydrofracturing crack initiated. By recording the pressure versus time curve, and observing the shape and orientation of the fracture, the magnitudes and orientations of the maximum and minimum principal stresses can be estimated. The vertical stress can be estimated from the weight of the overburden. The traditional hydraulic fracturing results can be evaluated using the Bredehoeft equations (Bredehoeft et al., 1976):

$$\begin{aligned}\sigma_h &= P_s \\ \sigma_H &= 3P_s - P_r - P_0 \\ \sigma_v &= \gamma H\end{aligned}\quad (1)$$

where σ_H (MPa) is the maximum horizontal principal stress, σ_h (MPa) is the minimum horizontal principal stress and σ_v (MPa) is the vertical stress. P_s , P_r , P_0 (MPa) are the shut-in pressure, reopening pressure and pore pressure respectively. γ (MN/m³) is average density of rock mass and H (m) is overburden thickness.

The classical theory of hydraulic fracturing stress measurement is based on the assumption that rock is homogeneous, isotropic, linearly elastic and non-permeable, and the fracture will reopen distinctly when the minimum tangential stress on borehole wall is exceeded. This theory has been further developed and revised by some scholars. Rutqvist et al. (2000) suggested that when an induced fracture is incompletely closed, the determination of the maximum principal stress by hydraulic fracturing using the reopening pressure has a high degree of uncertainty. Ito et al. (1999), stated that two sources of error exist in the estimation of the maximum horizontal stress using reopening pressure: the first arises from pressure penetration into the crack prior to reopening and the second concerns the correct identification of the true reopening pressure from the pressure records.

In this study, all the stress measurements were conducted in underground roadways. For planar stress measurements, boreholes were drilled upward in the middle of roadway roof to measure the maximum and minimum principal stresses on a horizontal plane, as illustrated in Fig. 1. Since the depth of boreholes is only 20–30 m, limited well storage can be obtained during the measurement process. The development of fractures can be closely controlled and fractures may obviously open during the first fracturing cycle which results in a strong possibility of the presence of completely closed fractures. In such a case, the maximum horizontal principal stress can be estimated

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