Implications of in-situ stress measurement in mining engineering

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Abstract. Knowledge of the in-situ stress conditions in mining areas is very necessary for scientific mining design and effective disaster control measures. The object of this article is to systematically introduce the in-situ stress measurement method and its implications in mining engineering, including mining design optimization, rockburst mechanism and prediction, stability control of surrounding rock, fault stability assessment, exploration and development of coalbed methane, coal and gas outburst prediction, evaluation of water inrush from coal floor, and high-stress rock breaking. The research results are of great significance to realize the safe, economic, and efficient recovery of mineral resources.

1. Introduction
The exploitation and utilization of mineral resources is the foundation of human survival and social development, and the mining industry has made important contributions to the development of human society. Mining engineering provides essential materials for human beings, but various engineering geological disasters occur frequently during mining due to artificial mining disturbance and complex hydrological and geological structural conditions, which seriously threatens the safe and efficient mining of mineral resources and the sustainable development of the mining industry.

In-situ stress is the natural stress that existed in the stratum before mining excavation and is the fundamental force causing deformation and failure of mining engineering [1,2]. The mining process involves a complex mechanical response process. In the process of mining excavation, the original equilibrium stress state of rock mass will be destroyed and a series of complex mechanical response behaviors related to stress redistribution will appear in the surrounding rock mass. All mining excavation activities and the corresponding mechanical responses, such as stress concentration of surrounding rock and deformation and movement of the rock mass, are carried out under the influence and control of the in-situ stress field [3]. To ensure the safety and efficiency of mining excavation and realize the optimization of mining design, the stability of surrounding rock in the entire process of mining excavation must be quantitatively calculated and scientifically analyzed. In-situ stress is the necessary mechanical precondition (boundary condition) for quantitative design and calculation. Therefore, the study of in-situ stress measurement and its distribution characteristics has always been a basic and quite important work in mining engineering.
2. In-situ stress measurement method
To understand the in-situ stress state of an interesting area, the most direct and effective way is to conduct the in-situ stress measurement. Since the concept of in-situ stress was proposed, the application of in-situ stress measurements in engineering construction and earth science research has been paid more and more attention. After several decades of development, a variety of in-situ stress measurement methods have been developed and applied worldwide, such as flat jacking, hydraulic fracturing, overcoring, strain recovery, borehole breakout, differential strain curve analysis, acoustic emission, acoustic observation, and geophysical methods [4]. These methods have their advantages and disadvantages, and their applicable conditions are also quite different.

In mining engineering, the commonly used in-situ stress measurement methods are overcoring and hydraulic fracturing methods, which are two highly maturing techniques recommended by the International Society for Rock Mechanics (ISRM) for characterizing the real stress state. The overcoring method uses casing drilling to relieve the stress of the drilling core. By monitoring the response of the strain or displacement of the relieved rock, and then the in-situ stress tensors can be determined according to the constitutive relationship of the rock (i.e., the relationship between the relieving strain or displacement and the far-field stress of the surrounding rock) with the knowledge of the elastic modulus and Poisson’s ratio of the rock [5]. This method has many advantages, such as high measurement accuracy, simple installation and operation, and low cost. The hydraulic fracturing method is an advanced method developed in the 1960s, which can be used to measure in-situ stress in deep holes. This method can directly measure the stress state in the rock mass without knowing the mechanical parameters of rock [6] and has the advantages of simple operation, continuous or repeated testing at any depth, fast measurement speed, and stable and reliable measured value, so it is widely used. For in-situ stress measurement in mines, hydraulic fracturing is the most economical and practical method in the early exploration stage of mines. Otherwise, if other methods, such as overcoring, are adopted, it needs to drill hundreds of meters deep pilot holes to approach the measuring points, which will be very expensive economically and therefore undesirable. However, during or after the construction of the underground mine, because there are a series of roadways, tunnels, and passages that can reach the measuring points, the overcoring method can be used for more detailed measurement, which can not only obtain more reliable and accurate in-situ stress data but also is the most reasonable in the economy.

3. Application of in-situ stress measurement in mining engineering

3.1. Mining design optimization
Knowledge of in-situ stress in the mining area is a necessary prerequisite for realizing scientific excavation design and decision-making of mining engineering [7]. In practice, it is often necessary to provide a good engineering design for an engineering scheme or to improve an engineering design without precedent. Only by mastering the stress state in the rock mass and the stress changes caused by engineering excavation can we truly achieve this. For mining engineering, only by understanding the in-situ stress conditions of specific mining areas can we reasonably determine the overall layout of mines, select appropriate mining methods, and determine the optimal cross-section shape, cross-section size, excavation steps, support forms, support structure parameters, support time, etc. of the roadway and stope, which has important engineering significance for ensuring the stability of surrounding rock, improving resource recovery rate, and realizing the optimization of mining engineering. For example, in the layout of the mining system, the direction of the underground roadway, stope, and chamber should be arranged as consistent or close as possible to the direction of maximum principal stress, which is conducive to the stability of roadway and stope and can reduce the support cost. When the production conditions are not allowed, the excavation direction of large-length and large-section openings should be avoided to intersect with the direction of maximum principal stress at a large angle. According to the elasticity theory, when the horizontal principal stress $\sigma_h$ is equal to the vertical principal stress $\sigma_v$, (figure 1), the optimal shape of the excavation section is
circular. Otherwise, the best shape of the excavation section is an ellipse. When the ratio of ellipse axis ratio (i.e., the ratio of the horizontal half axis $a$ to the vertical half axis $b$) is close to the ratio of $\sigma_h$ to $\sigma_v$ ((figure 1), the ellipse tends to be in the state of equal compression stress, which is beneficial to the stability of roadway [3]. This indicates that the shape of the excavation section should be as close to the circle or ellipse as possible according to the in-situ stress state and the actual production needs. Besides, the effect of in-situ stress should be fully considered in roadway support design. Roadway support design should be carried out based on the measurement of in-situ stress and other related parameters, and then the displacement, stress, and failure range distribution of the surrounding rock of roadway, as well as the stress state of supporting structure can be reasonably analyzed [8]. Furthermore, the influence of different factors on the deformation and failure of surrounding rock and the influence of different support parameters on the support effect can be clearly understood. Through the comparison of multiple schemes, the reasonable supporting form and parameters can be determined, so that the underground supporting effect and roadway safety can be reliably guaranteed.

![Figure 1](image-url)  
**Figure 1.** Schematic illustration of the optimal cross-section shape of horizontal roadway [3].

### 3.2. Rockburst mechanism and prediction

Rockburst is one of the most dangerous power disasters in mining engineering, which not only damages underground engineering structures and production equipment but also seriously threatens workers’ lives. The location of rockburst occurrence is “random”, the gestation process is “slow” and the occurrence process is “abrupt”. With the increase of mining depth, the frequency and intensity of rockburst are increasing, and its destructiveness to production safety is also increasing. The study of rockburst mechanism and its effective prediction have become a major technical bottleneck in mining engineering, and have been recognized as a worldwide problem in the field of rock mechanics.

Numerous studies have shown that rockburst is a mining dynamic disaster formed under the dominance of in-situ stress, which is the result of the accumulation and evolution of disturbance energy induced by mining excavation in surrounding rock and the sudden release of the energy when the surrounding rock breaks [9]. Before mining excavation, the stratum is in a state of natural equilibrium. Mining excavation causes the release of in-situ stress to the excavation space, forming an “equivalent release load” acting on the boundary of free space (figure 2), which leads to the deformation, movement, and local stress concentration of surrounding rock, and generates disturbance energy in the surrounding rock [10]. When the disturbance energy accumulated in rock mass reaches a high level and is suddenly released in the case of fracture of the surrounding rock, the impact failure, namely rockburst, will occur. This is an accurate understanding of the mechanism of rockburst. Therefore, the occurrence of rockburst must meet at least two necessary conditions [11]: one is that the mining rock mass must have the ability to store high strain energy and have a strong impact when it is destroyed; the other is that the surrounding rock of stope must have stress environment forming high strain energy accumulation. That is, essentially, the increase of stress level and the change of stress state are the fundamental factors leading to rockburst. The mechanism of rockburst discovered from the perspective of in-situ stress deepens the understanding of the basic connotation of rockburst occurrence and well explains how mining activities disturb the surrounding rock and how to cause disasters after the surrounding rock is disturbed.
On the other hand, rockburst is a kind of artificially induced earthquake caused by mining, which, like the natural earthquake, is a dynamic process of energy accumulation, evolution, and sudden release. The energy of natural earthquakes comes from the tectonic movement of the crust, while the energy of rockburst originates from the disturbance of mining and excavation. Therefore, with the knowledge of the in-situ stress measurements and the relationship between energy and magnitude in seismology [11], the potential rockburst trend and magnitude in the mining process can be predicted according to the calculated mining disturbance energy using the numerical method. This can provide a new idea and approach for the study of rockburst prediction.

Additionally, based on the mechanism of rockburst from the perspective of in-situ stress, it is pointed out that the core of rockburst prevention and control lies in reducing the high-stress concentration and high disturbance energy accumulation in the mining rock mass. By selecting reasonable mining methods, optimizing mining layout and mining sequence, improving the stress distribution in surrounding rock mass, and taking appropriate supporting measures, stress concentration and excessive displacement in the rock mass can be avoided, thus reducing and controlling the accumulation of mining disturbance energy and its disturbance effect on strata and faults and the subsequent rockburst occurrence [10]. At the same time, support measures that can absorb energy and prevent impact can be adopted to prevent and weaken the impact damage of rockburst.

3.3. Stability control of surrounding rock
The excavation of roadway in mining engineering will inevitably destroy the original three-dimensional stress equilibrium state of surrounding rock and redistribute the stress field and deformation field around the surrounding rock [12]. When the stress state of surrounding rock around the roadway exceeds the elastic limit of rock mass and enters the plastic stress state, four zones appear successively in the surrounding rock of the roadway from the free face to the outside, namely, ruptured zone, plastic softening zone, plastic hardening zone, and elastic zone (Figure 3) [13]. Under the action of the in-situ stress field, the released load drives the surrounding rock to deform towards the excavation free space. As the deformation exceeds a certain limit, it will cause damage to the surrounding rock, and even lead to instability, collapse, and impact damage of the surrounding rock in severe cases.

According to Mohr’s strength theory [14], rock failure is a kind of shear failure. The difference between the maximum principal stress and the minimum principal stress is closely related to the shear stress in the rock mass, which can reflect whether the surrounding rock is in a stable state to a certain extent. When the difference is large, the shear stress of rock mass is often large, and the possibility of shear failure is high. The high differential stress is an important factor affecting the stability of the underground surrounding rock. Hence, one of the most commonly used methods to control the stability of roadway surrounding rock is to change the stress conditions of surrounding rock (i.e., reduce the stress difference) and restrain the deformation of surrounding rock. By improving the stress distribution state, the unstable stress state can be changed into a stable stress state under the condition of constant rock mass strength. Referring to Mohr’s strength theory [14], the Mohr circle is reduced or moved to the right, so that it is below the strength curve (the surrounding rock is in a stable stress state). It is an important means to improve stress distribution by choosing reasonable roadway cross-
section shape and axial ratio and adopting reasonable supporting measures. In addition, to formulate and implement effective surrounding rock control measures, it is of great necessity to accurately know the in-situ stress conditions in mining areas. Countries all over the world have realized the importance of in-situ stress in controlling the stability of surrounding rock of stopes, roadways, and chambers. Comprehensive in-situ stress measurement campaigns have been performed before the mine construction or during the mining period and applied to the analysis and control of surrounding rock stability, and favorable results are achieved.

![Figure 3. Schematic illustration of failure zone around the roadway [13].](image)

3.4. Fault stability assessment

As a common geological structure in underground mines, the fault is a geological factor that cannot be ignored in underground mining and poses a great threat to mine safety production [7]. The complexity of fault development is closely related to the change of in-situ stress state, and the stability of fault is controlled by the stress condition. In-situ stress accumulation theory is widely used to evaluate the stability of faults. In-situ stress accumulation theory integrates Anderson’s fault theory, Coulomb’s friction criterion, and Byerlee’s law [15].

Anderson established three different stress regimes according to the magnitude relationship among $\sigma_H$, $\sigma_n$, and $\sigma_v$ and combined them with fault types, namely $\sigma_v > \sigma_H > \sigma_h$ is normal faulting stress regime, $\sigma_H > \sigma_v > \sigma_h$ is strike-slip faulting stress regime, and $\sigma_H > \sigma_h > \sigma_v$ is reverse faulting stress regime, which is known as the famous Anderson’s fault theory. Coulomb’s friction criterion indicates that when the mechanical state of a fault plane meets $\tau \geq \mu \sigma_n$, the fault is in an unstable state and will slip along a suitable plane, where $\tau$ is shear stress, $\mu$ is apparent fault friction coefficient and $\sigma_n$ is normal stress. To adopt the measured in-situ stress data for calculation, the concepts of effective stress, average stress, and maximum shear stress are introduced, and assuming that the cohesion of faults is 0, the ratio of maximum shear stress to average stress can be expressed as a function of $\mu$ [16]:

$$\frac{s_1 - P_0}{s_3 - P_0} = \left(\frac{1+\mu^2 + \mu^3}{1+\mu^2 + \mu^3}\right)$$

where $s_1$ and $s_3$ are the maximum principal stress and the minimum principal stress, respectively; $P_0$ is pore pressure.

Combined with Anderson’s fault theory, the mechanical stability conditions of reverse fault, strike-slip fault, and normal fault can be obtained:

$$\begin{align*}
\text{Reverse fault: } & \frac{s_1}{s_3} = \frac{s_H}{s_v} \leq \left(1 + \mu^2 + \mu^3\right)^{1/2} + \mu^2 \\
\text{Strike-slip fault: } & \frac{s_1}{s_3} = \frac{s_H}{s_h} \leq \left(1 + \mu^2 + \mu^3\right)^{1/2} + \mu^2 \\
\text{Normal fault: } & \frac{s_1}{s_3} = \frac{s_H}{s_h} \leq \left(1 + \mu^2 + \mu^3\right)^{1/2} + \mu^2
\end{align*}$$

(2)
According to Byerlee’s law, the friction coefficient $\mu$ of rock is basically 0.6-1.0 [17]. Subsequently, Eq. (2) can be used to qualitatively or semi-quantitatively evaluate the stability of different types of faults.

In addition, based on the in-situ stress measurement results, other methods such as numerical simulation and theoretical analysis can be used to quantitatively calculate the magnitude and direction of fault deformation and movement. On this basis, the stress condition acting on the fault can be changed by reasonable supporting measures, and the deformation and movement of the fault can be controlled within the allowable range. In particular, for faults with large sliding tendency, proper resistance must be given to prevent the sliding from causing engineering disaster.

3.5. Exploration and development of coalbed methane

In-situ stress is the main driving force for coalbed methane migration and accumulation, and the reservoir fractures, faults, and structures formed under the action of in-situ stress are the primary channels and places for coalbed methane migration and accumulation. The present-day in-situ stress field affects and controls the dynamic changes of coalbed methane in the process of coalbed methane development.

Permeability plays an important role in coal mining and coalbed methane development. Previous studies indicated that the in-situ stress has a significant influence on the permeability of coal reservoirs, the permeability of coal seam is extremely sensitive to in-situ stress, and the permeability decreases exponentially with the increase of in-situ stress [18]. In the exploration and development of coalbed methane, in-situ stress is the internal factor that leads to the strain, fracture, and permeability change of coal and rock mass, and is the primary factor that affects the permeability of coal reservoir, the essence of which is that in-situ stress affects the opening degree of joints and fissures [19].

In addition, by analyzing the relationship between in-situ stress and fractures, we can study the law of coalbed methane migration and accumulation and find a coalbed methane accumulation area. According to the distribution characteristics of in-situ stress and reservoir lithology parameters, the law of fracture propagation in hydraulic fracturing can be predicted to provide a basis for making a reasonable development plan of coalbed methane, and the coalbed pressure profile can be established to predict the wellbore stability of coalbed methane extraction project. Therefore, in-situ stress is an important basic data for coalbed methane development scheme design, and obtaining accurate in-situ stress data is of great significance for coalbed methane exploration and development.

3.6. Coal and gas outburst prediction

Coal and gas outburst is a kind of mine dynamic disaster that occurs in the coal-rock system under the mining disturbance, which poses a serious threat to coal mine safety production. The occurrence of coal and gas outburst is one of the most direct results of the in-situ stress effect. The current tectonic stress field and its evolution play a major role in coal and gas outburst, which determines the secondary migration and accumulation of gas and provides a mechanical environment for the gas outburst. Specifically, coal and gas outburst is a kind of energy release. In the process of outbursts, in-situ stress (including original rock stress, concentrated stress caused by excavation, and tectonic stress) breaks up the coal body, thus reducing the strength and increasing the cracks of the coal body. In-situ stress plays an important role in the initiation and development of coal and gas outburst in the following aspects [20]: (1) in-situ stress does work on surrounding rock and coal, increases the elastic deformation potential of the surrounding rock and coal, and causes sudden damage and displacement of coal; (2) in-situ stress field controls gas pressure field, promotes the role of gas in destroying coal, and increases gas pressure in stress concentration area; (3) the increase of stress in surrounding rock determines the low permeability of coal seam, resulting in the increase of gas pressure gradient, and once the coal body is destroyed, it will form favorable conditions for the outburst. Therefore, it will play a decisive role in predicting coal and gas outbursts and formulating reasonable measures to investigate the characteristics of the contemporary in-situ stress field in the mining area. For example, the prediction method of regional coal and gas outburst danger zone based on in-situ stress...
measurements [21] can effectively predict the potential danger zone in undeveloped areas, and take targeted preventive measures according to the predicted outburst danger degree, thus reducing the probability of coal and gas outburst disasters.

3.7. Evaluation of water inrush from coal floor [22]

The mine water inrush, especially the water inrush from the coal floor has always restricted the healthy development of the coal industry. In-situ stress is one of the important geological factors affecting water inrush from coal floor. Under the action of in-situ stress, the aquiclude zone mainly depends on its thickness and strength to resist the outburst of confined water. With the help of in-situ stress, the aquiclude zone with a certain thickness can make the fractures disconnected and prevent the rise of confined water. When the thickness of the aquiclude zone is large enough, the long-term dissolution of the rock stratum by water is not so terrible. Moreover, as the thickness of the aquiclude zone is greater than the depth of the influence of mine pressure on the rock mass of the working face floor, the in-situ stress will help prevent the water inrush from the coal floor. The strength of the aquiclude zone is mainly to prevent the floor from shear failure due to the combined action of strong mine pressure and water pressure. Because the tensile strength of the rock stratum is small, the confined water can effectively prevent the expansion and extension of cracks only under the action of in-situ stress, and the greater the in-situ stress is, the better it is to prevent water inrush from the floor. Therefore, the knowledge of the aquiclude zone and in-situ stress provides a potential method to evaluate whether water inrush occurs in the coal seam floor.

3.8. High-stress rock breaking

The drilling-blasting method is still widely used in high in-situ stress hard rock excavation in non-coal underground mines. Under the action of blasting load, the deformation of surrounding rock increases, and the failure evolution process becomes more complex, which seriously threatens the stability of the mining engineering structure. Consequently, while preventing and suppressing engineering disasters induced by high stress in the process of drilling and blasting, it is a further concern that how to control rock fragmentation and improve crushing quality by utilizing the fragmentation mutagenicity of high stress.

Under the action of high in-situ stress, roadway excavation will produce a wide range of failed zones and excavation disturbed zones around the roadway (figure 4), where rock strength decreases and cracks expand [23]. High in-situ stress is equivalent to prestress acting on rock mass, which makes rock mass become a high energy storage body. Under certain induced conditions, the deformation energy in rock mass will be released in the form of kinetic energy. High stress can accelerate the crack propagation and coalescence in the rock mass and the phenomenon of “easy to chisel and explode” in hard rocks under this condition, which brings convenience to break ore and rock in the stope. The high-stress environment becomes a favorable factor for non-explosive continuous mining. On the basis of making full use of the energy stored in the rock, the energy is expected to be transformed into the driving force for rock breaking under appropriate induced fracture projects and ways, and the non-explosive continuous mining can be realized without explosives or with fewer explosives, which can reduce the consumption of mine materials and the mining cost. Hence, the application of the high-stress disturbance rock breaking method to mining engineering has brought a good opportunity to improve the efficiency of rock breaking. In fact, Chinese researchers have begun the attempt of non-explosive mining in metal mines and achieved good results [24]. In the future, with more and more mines entering deep mining, the application prospect of non-explosive continuous mining method under high-stress conditions will be broader, which will help to change the traditional mining technology based on blasting in non-coal underground mines.
In conclusion, mining excavation will lead to the redistribution of the original in-situ stress state. The disturbance of any stope operation and engineering excavation will cause the stress change of the whole mining system. The stress redistribution is continuous during the entire mine service period, and the dynamic evolution effect of the in-situ stress field in the mine area is more significant. In addition, a mine is not only affected by the original in-situ stress field, but also by the action of mining stress field and supporting stress field, which form the comprehensive stress field in the mine [25], and the surrounding rock in the mine is subject to the superposition effect of the comprehensive stress field. Therefore, in the practice of mining engineering design and optimization, resource development, and disaster prevention and control related to in-situ stress, we should master the characteristics of in-situ stress distribution in the mining area instead of relying on simple experience analogy, which will be more conducive to the realization of scientific mining design and decision-making, and then to better recover mineral resources safely and efficiently.

4. Discussion
Knowledge of the in-situ stress including magnitude and orientation is important in many mining engineering issues, especially the above-presented problems. A series of valuable achievements have been made in the study of in-situ stress in the mining industry both in theory and application, which is an important step forward for us to understand the stress state of surrounding rock to improve our knowledge and methodologies of establishing a deterministic model of how mining activities disturb the stress field and cause subsequent mechanical responses.

Due to the interaction of various influencing factors near the earth’s surface, the measured in-situ stress often overlaps with non-structural stress. Therefore, before in-situ stress measurement, it is necessary to analyze the influence of topography, fracture, engineering disturbance, and other factors, and determine the distribution and depth of measurement position in the undisturbed area, so that the measured stress state can be free from the influence of non-tectonic stress, thus improving the accuracy and reliability of in-situ stress measurement results. When applying in-situ stress measurement results to mining engineering-related problems such as mining design, disaster prediction and prevention, resource exploitation, non-explosive continuous rock breaking, etc., we should fully consider the differences of geological conditions and the changes of in-situ stress state caused by different mining activities, so that the measured in-situ stress results can better serve mine production.

Given the complexity of the mining system, the adjustment and redistribution of stress fields corresponding to mining activities, and the geological bodies, we have not fully grasped the change characteristics of in-situ stress state and its disaster-causing mechanism in the mining process, which leads to some blindness in the application of in-situ stress analysis to related engineering problems, and some problems have not been reasonably explained or well solved. As a result, mining engineering disasters occur from time to time. Especially, guiding the exploitation of coalbed methane resources and other additional resources according to the characteristics of stress field or using high stress to break rocks is still in the initial exploratory stage, and the relevant guiding theory has not yet been established, so these aspects need to be further studied.
5. Conclusion
Underground mining is a very complicated multi-step excavation process, and all mining excavation activities are carried out under the control of in-situ stress. Accurately grasping in-situ stress state in mining area is a necessary prerequisite for realizing scientific excavation design and decision-making, predicting and preventing mine disasters as well as changing mining technology. In this article, the in-situ stress measurement methods and the specific applications of in-situ stress measurement in mining design optimization, rockburst mechanism and prediction, stability control of surrounding rock, fault stability assessment, exploration and development of coalbed methane, coal and gas outburst prediction, evaluation of water inrush from coal floor, and high-stress rock breaking were summarized, which can provide scientific guidance for the safe and efficient development of mineral resources in the future.

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References
[1] Li P and Miao S J 2016 Analysis of the characteristics of in-situ stress field and fault activity in the coal mining area of China J. China Coal Soc. 41 319–29
[2] Li P and Miao S J 2017 Analysis and application of in-situ stress in metal mining area of Chinese mainland Chinese J. Eng. 39 323–34
[3] Cai M F 2020 Key theories and technonogies for surrounding rock stability and ground control in deep mining J. Min. Strat. Control Eng. 2 5-13
[4] Cai M F, He M C and Liu D Y 2002 Rock mechanics and engineering (Beijing: Science Press)
[5] Li P, Ren F, Cai M, Guo Q and Miao S 2019 Present-day stress state and fault stability analysis in the capital area of China constrained by in situ stress measurements and focal mechanism solutions. J. Asian Earth Sci. 185
[6] Li P and Cai M 2018 Distribution law of in situ stress field and regional stress field assessments in the Jiaodong Peninsula, China. J. Asian Earth Sci. 166 66–79
[7] Li P, Cai M, Guo Q and Miao S 2018 Characteristics and implications of stress state in a gold mine in Ludong area, China Int. J. Miner. Metall. Mater. 25 1363–72
[8] Kang H P, Jiang T M, Zhang X and Yan L X 2009 Research on in-situ stress field in Jincheng mining area and its application Chinese J. Rock Mech. Eng. 28 1–8
[9] Miao S J, Cai M F, Guo Q F and Huang Z J. 2016 Rock burst prediction based on in-situ stress and energy accumulation theory Int. J. Rock Mech. Min. Sci. 83 86–94
[10] Cai M F 2016 Prediction and prevention of rockburst in metal mines – A case study of Sanshandao gold mine J. Rock Mech. Geotech. Eng. 8 204–11
[11] Cai M F, Ji D and Guo Q F 2013 Study of rockburst prediction based on in-situ stress measurement and theory of energy accumulation caused by mining disturbance Chinese J. Rock Mech. Eng. 32 1973–80
[12] Sagong M, Park D, Yoo J, and Lee J S 2011 Experimental and numerical analyses of an opening in a jointed rock mass under biaxial compression Int. J. Rock Mech. Min. Sci. 48 1055–67
[13] Wang W J, Yuan C, Yu W J, Wu H, Peng W Q, Peng G, Liu X S, and Dong E Y 2016 Stability control method of surrounding rock in deep roadway with large deformation. J. China Coal Soc. 41 2921–31
[14] Jaeger J C, Cook N G W, and Zimmerman R 1979 Fundamentals of rock mechanics. Chapman and Hall Press, London
[15] Li P, Guo Q F, Liu H T and Jiang X Q 2017 Characteristics of current in-situ stress field and
stress accumulation in Shandong region *Chinese J. Rock Mech. Eng.* **36** 2220–31
[16] Li P, Cai M F, Miao S J and Guo Q F 2019 New insights into the current stress field around the Yishu fault zone, eastern China *Rock Mech. Rock Eng.* **52** 4133–45
[17] Li P, Cai M, Guo Q and Miao S 2019 In situ stress state of the northwest region of the Jiaodong Peninsula, China from overcoring stress measurements in three gold mines *Rock Mech. Rock Eng.* **52** 4497–507
[18] Sun Z L, Kang Y S, Wang J, Jiang S Y, Zhang B and Gu J Y 2017 Vertical transformation of in-situ stress types and its control on coalbed reservoir permeability *Geol. J. China Univ.* **23** 148–56
[19] Wen Z, Kang Y S, Deng Z, Li G Z, Wang H Y and Cao M L 2019 Discussion on the regional distribution law of coal permeability in China and the relationship with in-situ stress *2019 Sym. Coal. Meth.* **12** 274–85
[20] Gao K, Liu Z G and Liu J 2015 Effect of geostress on coal and gas outburst in the uncovering tectonic soft coal by cross-cut *Chinese J. Rock Mech. Eng.* **34** 305–12
[21] Sun D S, Wang L J, Zhao W H and Wang H C 2010 The application of in-situ stress measurement to the study of coal and gas outburst in coal mines *Geol. China* **37** 223–8
[22] Li J X, Li D P, Zhang W Q and Liu W T 1999 The relations of initial geostress and water irruption of seam floor *Chinese J. Rock Mech. Eng.* **18** 419–23
[23] Read R S 2004 20 years of excavation response studies at AECL’s Underground Research Laboratory *Int. J. Rock Mech. Min. Sci.* **41** 1251–75
[24] Li X B, Yao J R and Du K 2013 Preliminary study for induced fracture and non-explosive continuous mining in high-geostress hard rock mine–A case study of Kaiyang phosphate mine. *Chinese. J. Rock Mech. Eng.* **32** 1101–11
[25] Kang H P 2008 Analysis on types and interaction of stress fields in underground mines *J. China Coal Soc.* **33** 1329–35