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ORIGINAL PAPER

Analysis of the distribution characteristics and laws of in situ stress in China's coal mines

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Abstract

Based on the measured in situ stress data in China's coal mines, the relationship among the type of stress field, magnitude of stress, stress value, and the depth of burial was analyzed. The trends in the changes in side pressure coefficient and side pressure ratio were regressed and fitted with the increase in depth. This was compared to the Hoek-Brown curve, and the distribution characteristics and variation laws of underground stress field in China's coal mines were determined. (1) Generally, in situ stress increases with burial depth, but the geological structure and lithology render horizontal stress considerable. (2) In 87.72% of stress fields, which are considered typical tectonic stress fields, the horizontal stress comes into prominence. (3) About 64% working environment is the middle- and high-stress zones, and low- and ultrahigh-stress zones account for about 18% each. (4) The ratio of horizontal principal stress was distributed within a range of 1.0~2.5, and it was affected very little by burial depth. However, the difference increased continuously with burial depth, causing an obviously growing shear failure of coal and rock. (5) The side pressure coefficient is mostly distributed in 0.9~2.0, and it decreases with burial depth and is gradually close to 1.32. (6) Most side pressure ratio is in 0.5~1.6. When the burial depth is less than 700~750 m, the horizontal principal stress is lower than one in the world. Conversely, the magnitude of horizontal principal stress was more pronounced in deeper areas, but it always plays a leading role in the in situ stress field. (7) The seismic belt has a great influence on coalfield stress fields. Without affecting the stress field, the direction of maximum principal stress is approximately parallel or perpendicular to the trajectories of principal stress in China Continental Plate. However, under the composite effect of geological structure, the direction changed visibly. There is no apparent relationship between the two and no law to follow. The statistics of in situ stress are important reference values for understanding stress distribution in China's coal mines, and it also has a practical guiding significance for safely and efficiently mining underground.

Keywords Coal mines · The original rock stress measurement · Stress field · Distribution characteristics and laws · Regression analysis · Seismic belt

Introduction

In situ stress is a natural stress that occurs in rock formations and is not affected by engineering projects. It is also known as the initial stress of rock or original rock stress. Because it is an internal stress, it is formed in the rock's long geological evolution and a multiple stacking result of gravity field and tectonic stress fields. Consequently, the rock's stress state is very complex and changeable.

The stress field is mainly composed of gravity fields and tectonic stress fields. The gravity field is caused by the weight of overlying strata and it is relatively simple. Its magnitude can be estimated by the weight of overlying strata in the unit area and burial depth. The tectonic stress fields are not only related to burial depth but also closely associated with

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geological structure and its movement. The horizontal movement of geological structure has an especially great influence on the formation and distribution of stress fields (Cai et al. 2002; Li et al. 2008; Wang et al. 2010a, b, c; Zhao et al. 2007). The factors affecting tectonic stress fields are very complex, and they include the type, scale, time, space evolution, activity status, and number of times of tectonic movement (Han and Cai 2007; Jiang et al. 2011a, b; Kang et al. 2012; Miao et al. 2012; Samuel et al. 2015). So the distribution of tectonic stress field is very uneven in space. It changes constantly over time. Time and space both have a certain effect on the nonstable stress field (Leont'ev et al. 2013; Tian et al. 2015; Zhao et al. 2007). It is currently very difficult to describe the functions of the distribution characteristics and variation laws of tectonic stress fields. A relatively reliable and feasible method is site measurement. Based on the measured data, statistics and analysis can be performed to search for stress distribution laws suitable for guiding engineering in practice (Huang et al. 2014; Kang et al. b; Liu et al. 2014a, b, 2016; Li et al. 2014a, b; Suman and Rima 2011a, b; Talebi et al. 2015; Wang et al. 2012, Wang et al. 2014; Zhao 2014; Zhao et al. 2012, 2013).

In situ stress is a fundamental power causing the deformation of surrounding rock and failure of underground engineering projects, such as coal mines. It is also an important base parameter for mine design, the layout and optimization of roadways, and the dynamic design of roadway support (Huang 2012; Li et al. 2013a, b; Ptacek et al. 2015; Pu et al. 2005; Wang 2012; Yin 2012; Yang 2012; Zhang and Han 2006; Zhang et al. 2008).

It is also one of the main causes for rock bursts (Song et al. 2012; Tang et al. 2002; Zhou et al. 2004) and the outburst of coal, rock, gas, and water (Cai et al. 2009; Dariusz 2009; Han et al. 2012; Mortimer et al. 2011; Miao et al. 2016; Qin et al. 2014; Yang et al. 2014; Yang et al. 2012; Yin et al. 2015; Zhang and Ma 2002). As a consequence, understanding the distribution characteristics and laws of in situ stress is highly relevant to the safety and efficient operation of coal mines.

China's coalfields vary significantly. Because of the influence faults, folds, collapse columns, even seismic belts, and the tremendous difference of mining conditions in each mining areas, the stress distribution of coal-bearing strata is very complex (Kuznetsov and Trofimov 2003; Kang et al. b; Liu 2011a, b; Suchowerska et al. 2014). Take the burial depth of coal seam for instance. The mining depth of some western mines is only tens of meters, but it has reached 1600 m in East China, leading to a dramatic discrepancy in stress size and distribution and an essential difference in the deformation and failure pattern of the surrounding rock.

In recent years, the scale of underground coal mines in China has been expanding and coal has been mined at greater depths. Naturally, the influence of in situ stress on mine safety has become increasingly prominent (Cai et al. 2012; Liu et al. 2014a, b). In this way, the measurement and study of the distribution of in situ stress in coal mines are vital to mine construction and safe operation.

Measurement of in situ stress in China

China has focused on the measurement of in situ stress later than other countries. It was in the late 1950s that the Institute of Geological Mechanics led by S.G. Li and Three Gorges Bedrock Research Group led by Z.J. Chen began to explore the related fields. In 1964, the first stress relief measurement, whose measurement depth was 80 m, was implemented by Wuhan Institute of Rock and Soil Mechanics at the Chinese Academy of Sciences at the Daye iron mine in Hubei Province. In March 1966, a piezomagnetism stress meter was successfully developed for the detection of absolute stress at the Institute of Geology of the Chinese Academy of Geological Sciences, and stress observation stations were set up in succession in Longyao, Hebei Province, in total 21 provinces, municipalities, and autonomous regions. In the 1970s, the measurement of in situ stress was mainly used by the department of water conservancy and hydropower. In the early 1980s, the hydraulic fracturing method was introduced from the USA by the Institute of Crustal Stress. Later, a stress measurement device of a hollow inclusion strain gauge was brought in again, and an in-depth research was done. Finally, various hollow inclusion strain gauges, which were completely designed and manufactured by China, were developed, and they were fully applied to site measurement. In the 1990s, the technology for the measurement of in situ stress continued to mature, and it became widely applied in geotechnical and underground engineering. In the early years of the twenty-first century, the measurement of in situ stress in coal mines underwent rapid development, and a good deal of site measurement has been carried out (Li 2014; Liu 2014; Qiao 2014; Wang 2014).

There are currently several methods of measuring in situ stress. Because of the geological structures and the destruction conditions of underground rock strata, different methods have their own limitations (Liu 2014; Qiao 2014). At present, the stress relief method, hydraulic fracturing method, and acoustic emission method are widely used to measure in situ stress in coal mines in China. And the characteristics of these methods are shown in Table 1.

Analysis of in situ stress in China's coal mines

Based on the existing measurement of in situ stress in China's coal mines, 578 sets of data were collected in this paper in total (Bai 2010; Bai et al. 2005; Cai 2007; Chang 2010; Cai et al. 2004, 2006, 2008, 2009; Chen et al. 2011; Cui et al. 2011;

Table 1 Summary of the popular measurement methods for in situ rock stress

Measurement method	Advantage	Disadvantage	Application scope
The stress relief method	High accuracy	Limited measurement points and potential technical difficulty	The existing roadway and chamber
The hydraulic fracturing method	Simple equipment, convenient operation, great representativeness, strong adaptability, and big depth	Low accuracy, high cost, and bad direction of principal stress	Larger scope
The acoustic emission method	Low labor intensity, high integrity of study area, and repeatable measurement	Limited application scope and low accuracy	High strength brittle rock

Diao 2002; Dai et al. 2003; Fan et al. 2007; Gong et al. 2008; Gou and Zhang 2002; Huang 2012; Han and Cai 2007; Hu et al. 2012; Han and Zhang 2009; Han et al. 2008; Jiang et al. 2011a, b; Jin and Xian 1994; Jiang et al. 2011a, b; Kang et al. 2009a; Kou and Lv 2012; Kong et al. 2003, 2005, 2007, 2009b, c, 2010a, 2012; Liu 2011a, b; Luo 2009; Liu 2009; Li and Ding 1992; Li et al. 2002; Li and Li 2006, 2011; Li and Lin 2005; Liu and Liu 2012; Liu and Li 2006; Liu et al. 2009; Li et al. 2013a, b; Liu et al. 2011a; Liu et al. 2011a, b; Li et al. 1998; Li et al. 2008; Liang et al. 2010; Li et al. 2004; Meng et al. 2011; Meng and Wang 2011; Ma et al. 2011; Ma et al. 2010; Nan et al. 1998; Ni et al. 2008; Peng et al. 2011; Pan et al. 2010; Pang et al. 1991; Pu et al. 2005; Qi and Tang 2011; Qu and Han 2011; Qi et al. 2010; Ren 2005; Sun 2012; Sui et al. 2009; Song et al. 2012; Tan 2013; Tang et al. 2002; Tian and Wei 1990; Wang 2011; Wang et al. 2013; Wei et al. 2007; Wang and Lei 2012; Wang and Liu 2010; Wang et al. 2010a, b; Wu et al. 2008; Wang and Su 2009; Wu et al. 2004; Wang et al. 2010c; Wang et al. 2011; Wu et al. 2006; Xu 2010a, b; Xie 2012; Yin 2012; Yang and Fu 1999; Yu et al. 2010; Yan et al. 2013; Zhang 2012a, b, c; Zheng 2010; Zhu 2007; Zhang 2010; Zhang et al. 2004; Zhou et al. 2004; Zhang and Han 2006; Zhang et al. 2008; Zhang et al. 2010; Zhang and Lin 1997; Zhou et al. 2005; Zhao et al. 2008; Zheng and Wang 2011; Zhao et al. 2011; Zheng et al. 2008), in which, the hydraulic fracturing method and stress relief method are more widely used, accounting for 53.11% and 40.14% of the statistical data respectively, as shown in Table 2. The specific distribution is shown in Fig. 1.

According to the measurement distribution of in situ stress, it is necessary to explain something: in the early 2000s, the measurement research on in situ stress in China's coal mines underwent rapid development, and stress was measured at many mines. Because of factors such as the national exploitation orientation of coal resources, coal occurrence, and coal reserves, the measurement conditions of in situ stress differ considerably in different areas.

(1) In 2000~2010 years, coal mining has mainly been concentrated in China's central eastern area. So, a large number of measured data are basically from these coalfields including Shandong, Shanxi, Henan, Anhui, and Xuzhou, accounting for 78.72%. Although the northwest is rich in coal reserves, the measured in situ stress data is less (12.98%). With the shift of mining focus, the in situ stress measurement will be the key basic work in this area.
(2) In northeastern China, coal mining began in the early twentieth century. By the end of that century, coal resources were on the verge of exhaustion, so relatively little measurement (2.27%) had been carried out.
(3) Owing its few coalfields and generally low production, in situ stress (2.25%) seldom has been measured in the southwest.
(4) There are no coalfields in southern China, so, naturally, nothing is related to in situ stress has been done.
(5) 1.1 Type characteristics of in situ stress field

Due to the influence of burial depth and geological structure, there are considerable differences in the in situ stress fields of different coalfields and mining areas. These principal stresses can be divided into the following categories by type of principal stress: (1) the horizontal principal stress is dominant, namely $\sigma_H > \sigma_v > \sigma_h$ or $\sigma_H > \sigma_h > \sigma_v$; (2) the vertical principal stress is preferential, namely $\sigma_v > \sigma_H > \sigma_h$. The type statistics of stress field are shown in Table 3. A total of 87.72% stress fields are dominated by horizontal principal stress. Those stress fields, in which tectonic stress plays a dominant role, are considered typical tectonic stress fields. A small number of vertical stress fields are intensively distributed in these coalfields, such as Xinwen, Qinshui, Hedong, Huoxi, Ningwu, Huainan, Pingdingshan, and Tuha. The research shows that the influence of tectonic stress field on mining is often greater than that of vertical stress field.

Magnitude characteristics of in situ stress

On the basis of the criteria proposed by Prof. Yu, the stress of 0~10 MPa was considered low, 10~18 MPa middle, 18~30 MPa high, and stress over 30 MPa ultrahigh (Yu et al. 1993). In 578 measurement points, the magnitude statistics of in situ stress is given in Table 4. About 64% of China's

Table 2 Statistics of in situ stress in China's coal mines

Province	Shandong (18.34%)					Shanxi (32.53%)				
Coalfield	Juye	Yanzhou	Xinwen	Longkou	Jining	Qinshui	Huoxi	Datong	Hedong	Ningwu
Quantity	67	20	13	5	1	118	46	9	8	7
Province	Anhui (15.05%)		Henan (6.57%)				Jiangsu (6.23%)	Hebei (5.36%)		
Coalfield	Huainan	Huaibei	Pingdingshan	Yongxia	Hebi	Jiaozuo	Xuzhou	Kailuan	Hanxing	Jingxi
quantity	69	18	30	5	2	1	36	20	7	4
Province	Shanxi, Inner Mongolia (2.25%)		Gansu (4.33%)	Ningxia (1.73%)	Xinjiang (3.11%)	Guizhou (0.87%)	Helongjiang (0.35%)	Liaoning (2.25%)	Chongqing (0.69%)	Jilin, Hunan (0.35%)
Coalfield	Shenfudongsheng	Zhunge'er	Huating	Ningdong	Tuha	Zhina	Hegang			
quantity	9	4	25	10	18	5	2	13	4	1, 1

coal mining operations are in middle- and high-stress zones, and the low- and ultrahigh-stress zones account for about 18% each. Low-stress zones are mainly in Qinshui, Huoxi, Ningwu, Huaibei (part), Jiaozuo, Shenfudongsheng, Zhunge'er, Ningdong, Tuha, and Zhina, in which coal seams are shallow-buried. The ultrahigh-stress zones are mainly distributed in deep coalfields including Juye, Hebi, Xinwen, Yong Xia, Xuzhou, and Kailuan. Practice has shown that there are no coal mines with a tendency of rock burst, coal and gas outburst in low-stress areas, and they may be transformed into the mines with frequent coal and gas outburst disasters after entering high- or ultrahigh-stress areas; under the complex high-stress conditions, the support and maintenance of roadway surrounding rock is difficult. According to

Fig. 1 Statistics and distribution of in situ stress in China's coal mines

Table 3 Type statistics of in situ stress field

Province	Shandong					Shanxi				
Coalfield	Juye	Yanzhou	Xinwen	Longkou	Jining	Qinshui	Huoxi	Datong	Hedong	Ningwu
Quantity	67	20	13	5	1	118	46	9	8	7
H > v	67 (100)	19 (95)	9 (69.23)	5 (100)	1 (100)	99 (83.9)	35 (76.09)	9 (100)	7 (87.5)	3 (42.86)
v > H		1 (5)	4 (30.77)			19 (16.1)	11 (23.91)		1 (12.5)	4 (57.14)
Province	Anhui		Henan				Jiangsu	Hebei		
Coalfield	Huainan	Huaibei	Pingdingshan	Yongxia	Hebi	Jiaozuo	Xuzhou	Kailuan	Hanxing	Jingxi
Quantity	69	18	30	5	2	1	36	20	7	4
H > v	55 (79.71)	18 (100)	20 (66.67)	5 (100)	2 (100)	1 (100)	35 (97.22)	20 (100)	7 (100)	4 (100)
v > H	14 (20.29)		10 (33.33)				1 (2.78)			
Province	Shanxi, Inner Mongolia		Gansu	Ningxia	Xinjiang	Guizhou	Helongjiang	Liaoning	Chongqing	Jilin, Hunan
Coalfield	Shenfudongsheng	Zhunge'er	Huating	Ningdong	Tuha	Zhina	Hegang			
Quantity	9	4	25	10	18	5	2	13	4	1, 1
H > v	9 (100)	4 (100)	23 (92)	10 (100)	15 (83.33)	5 (100)	2 (100)	13 (100)	4 (100)	1 (100), 1 (100)
v > H			2 (8)		3 (16.67)					

In A (B), A is the quantity of measurement points under certain condition, and B is the percentage of A accounting for the total statistics; the below text applies equally

incomplete statistics, the actual repair proportion of deep roadway is as high as 90% or more. While rock burst and coal and gas outburst work together, multiple factors are intertwined. In the process of gestation, occurrence, and development, they may be inducements to each other, strengthen each other, or produce resonance effect, which makes disaster prediction and prevention more complicated and difficult.

Table 4 Magnitude statistics of in situ stress

Province	Shandong					Shanxi				
Coalfield	Juye	Yanzhou	Xinwen	Longkou	Jining	Qinshui	Huoxi	Datong	Hedong	Ningwu
Quantity	67	20	13	5	1	118	46	9	8	7
≤ 10		3(15)				43 (36.44)	19 (41.3)			7 (100)
10~18		8 (40)		5 (100)		69 (58.47)	21(45.65)	8 (88.89)	2 (25)	
18~30	12 (17.91)	9 (45)	4 (30.77)		1 (100)	6 (5.08)	6 (13.04)	1 (11.11)	6 (75)	
≥ 30	55 (82.09)		9 (69.23)							
Province	Anhui		Henan				Jiangsu	Hebei		
Coalfield	Huainan	Huaibei	Pingdingshan	Yongxia	Hebi	Jiaozuo	Xuzhou	Kailuan	Hanxing	Jingxi
Quantity	69	18	30	5	2	1	36	20	7	4
≤ 10		4 (22.22)				1 (100)	1 (2.78)		1 (14.29)	
10~18	19 (27.54)	5 (27.78)	10 (33.33)				5 (13.89)	2 (10)	3 (42.86)	
18~30	48 (69.57)	9 (50)	17 (56.67)	2 (40)	1 (50)		17 (47.22)	8 (40)	2 (28.57)	4 (100)
≥ 30	2 (2.9)		3 (10)	3 (60)	1 (50)		13 (36.11)	10 (50)	1 (14.29)	
Province	Shanxi, Inner Mongolia		Gansu	Ningxia	Xinjiang	Guizhou	Helongjiang	Liaoning	Chongqing	Jilin, Hunan
Coalfield	Shenfudongsheng	Zhunge'er	Huating	Ningdong	Tuha	Zhina	Hegang			
Quantity	9	4	25	10	18	5	2	13	4	1, 1
≤ 10	9 (100)	4 (100)		7 (70)	7 (38.89)	3 (60)				
10~18			8 (32)	1 (10)	11 (61.11)	2 (40)		2 (15.38)	1 (25)	
18~30			17 (68)				2 (100)	8 (61.54)	3 (75)	1 (100), 1 (100)
≥ 30				2 (20)				3 (23.08)		

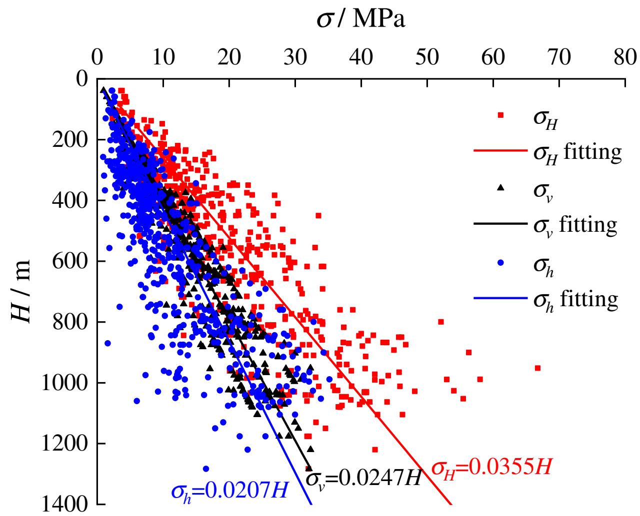

Fig. 2 Statistics of the measured in situ stress

Relationship between principal stress and burial depth

As shown in Fig. 2, the principal stresses gradually increase with the burial depth of measurement points. However, due to the influence of geological structure (faults, joints, folds, and collapse columns) and lithology, the horizontal principal stresses showed considerable discreteness and their distribution laws were not obvious.

Relationship between horizontal principal stress and burial depth

With the change in burial depth, the ratio of the maximum horizontal principal stress and the minimum horizontal principal stress ($k = \frac{\sigma_H}{\sigma_h}$) is shown in Fig. 3.

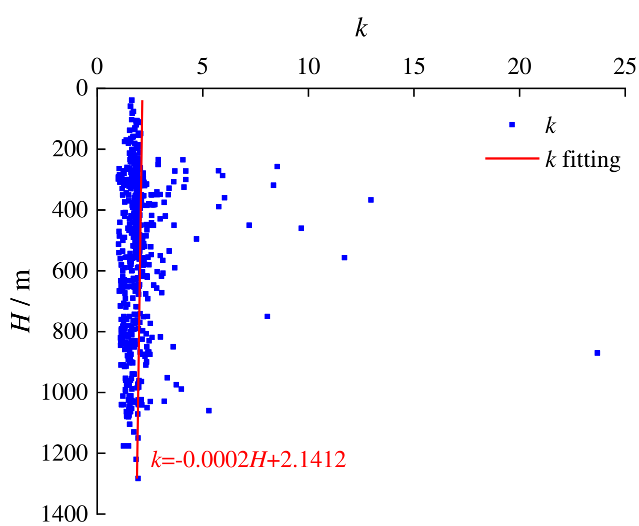

Fig. 3 Relationship between the ratio of horizontal principal stress and burial depth

With the depth of measurement points changing, the trend expression of the ratio of the horizontal principal stress is

$$k = -0.0002H + 2.1412 \tag{1}$$

From formula (1), the ratio of the horizontal principal stress is concentrated in 1.0~2.5, and the influence of burial depth is very little. The ratio decreases with burial depth, but the decreasing speed is very slow. Under the condition of current mining depth, the ratio is approximately 2.

Based on the theory of rock mechanics, another kind of stress is formed by the difference generated by the horizontal principal stress. It is exactly the stress that causes the coal and rock to be destroyed. Generally, it is defined as shear failure. The maximum shear stress is half the difference generated by the maximum and the minimum principal stress.

$$\tau = \frac{1}{2}(\sigma_H - \sigma_h) \tag{2}$$

The larger the ratio of horizontal principal stress, the greater the difference between the two. Accordingly, the shear stress was also larger and its directivity more conspicuous, which would result in more severe damage to coal and rock. On the basis of formula (2), the relationship between the maximum shear stress and burial depth was obtained, as shown in Fig. 4.

As the burial depth increased, the trends in the expression of the maximum shear stress were fitted as follows:

$$0.0008H + 0.4104 \le \tau \le 0.0101H + 2.1597 \tag{3}$$

In formula (3), the maximum shear stress increases with burial depth. In the shallow-buried areas, the shear stress is inconspicuous, contributing to coal and rock destroying little. The destruction effect will gradually become visible as burial depth increases.

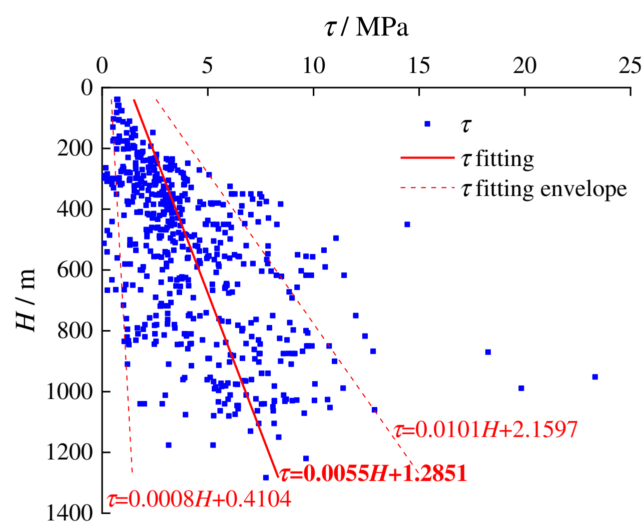

Fig. 4 Relationship between the maximum shear stress and burial depth

Relationship between vertical principal stress and burial depth

he practice indicates that the vertical principal stress is basically equal to or slightly less than the weight of overlying strata in the unit area. Referring to the measurement results of in situ stress in different parts of the world, E.T. Brown and E. Hoek summarized the law between vertical principal stress and burial depth and it is expressed as follows (Brown and Hoek 1978):

$$\sigma_v = 0.027H \tag{4}$$

The statistics of vertical principal stress in China's coal mines are shown in Fig. 5.

The relationship between vertical principal stress and burial depth is described as follows:

$$\sigma_v = 0.0247H \tag{5}$$

Formula (4) was compared to formula (5). Their growth trends were identical, but formula (5) increased less than formula (4) did (Hoek-Brown curve), which makes it clear that the vertical stress in China's mining areas is lower than one in the world.

From here, it can be seen that in situ stress increases with burial depth in China's mining areas. The greater the burial depth, the greater the magnitude of the stress and the more significant the directivity of principal stress, which brings about more serious shear damage to ore body and rock. So, as burial depth increased, the difficulty of underground mining operation also increased.

Relationship between side pressure coefficient and burial depth

The side pressure coefficient is the ratio of the maximum horizontal principal stress and the vertical principal stress, i.e.,

$$\lambda = \frac{\sigma_H}{\sigma_v} \tag{6}$$

The relationship between side pressure coefficient and burial depth is given in Fig. 6.

The side pressure coefficient is mainly distributed in 0.9~2.0. With the increase in burial depth, its change trend can be fitted as

$$\lambda = \frac{66.53}{H} + 1.32 \tag{7}$$

Formula (7) tells that the side pressure coefficient decreases with burial depth. As burial depth increases, the side pressure coefficient would gradually decrease and be eventually close to $\lambda = 1.32$. It manifests that under the current depth of coal mining in China, the horizontal principal stress generally comes into prominence in stress field, being consistent with the conclusion drawn in the "Type characteristics of in situ stress field" section.

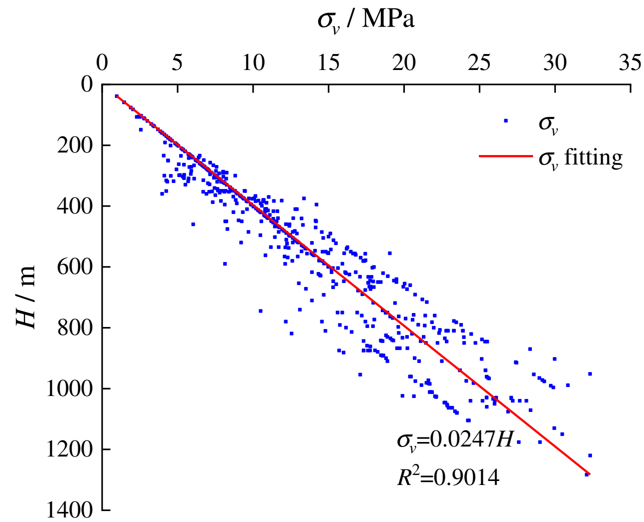

Fig. 5 Relationship between vertical principal stress and burial depth

Relationship between side pressure ratio and burial depth

The pressure ratio is calculated by the average horizontal principal stress and the vertical stress, and it is defined as follows:

$$\kappa = \frac{\sigma_H + \sigma_h}{2\sigma_v} \tag{8}$$

Hoek and Brown summarized and analyzed the relevant in situ stress in the world, the relationship between the side pressure ratio and burial depth was determined, and its expression is as follows (Brown and Hoek 1978):

$$\kappa = \frac{800}{H} + 0.4 \tag{9}$$

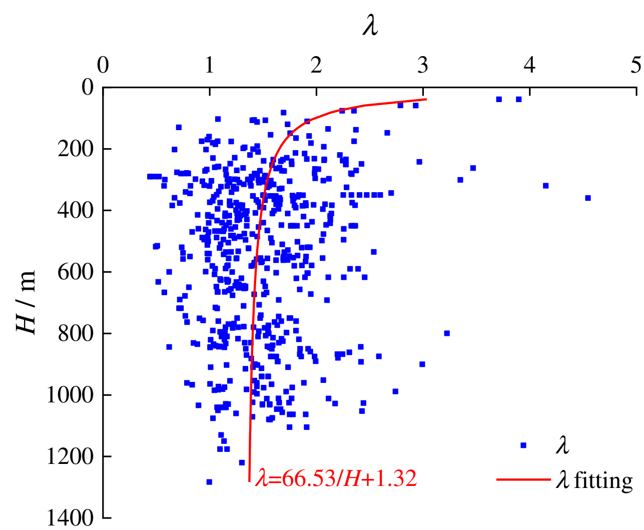

Fig. 6 Relationship between side pressure coefficient and burial depth

Meanwhile, the inner and outer envelope was also put forward and the formula is as follows:

$$\frac{100}{H}+0.3\leq\kappa\leq\frac{1500}{H}+0.5 \tag{10}$$

Combined with the statistics of in situ stress in China's coal mines, the relationship between the side pressure ratio and burial depth and the fitting envelope is given in Fig. 7.

The majority of side pressure ratios are within 0.5~1.6. With burial depth increasing, its change can be described as follows:

$$\kappa=\frac{202.45}{H}+1.2 \tag{11}$$

The inner and outer envelope are fitted as follows:

$$\frac{70.1}{H}+0.2\leq\kappa\leq\frac{334.8}{H}+2.2 \tag{12}$$

Formulas (9)~(12) were compared. Overall, the relationship between the side pressure ratio and burial depth in China's coal mines is similar to the Hoek-Brown curve. However, there are some marked differences in numerical value. When burial depth is less than about 750 m, the side pressure ratio is below Hoek-Brown. When it is over 750 m, the opposite is true. The outer envelope is located on the outside of Hoek-Brown curve. However, the inner envelope is the outside of Hoek-Brown curve when burial depth is less than 700 m. It is the inside of the Hoek-Brown curve under other circumstances. Analysis shows that the magnitude of horizontal principal stress in China's coal mines in the shallow-buried areas is less than one in the world (usually the burial depth is less than 700~750 m), but it constitutes an overwhelming superiority in the stress field. In deep areas, it is opposite about the magnitude of horizontal principal stress, but the horizontal principal stress still plays a leading role in the stress field due to a very small decrease.

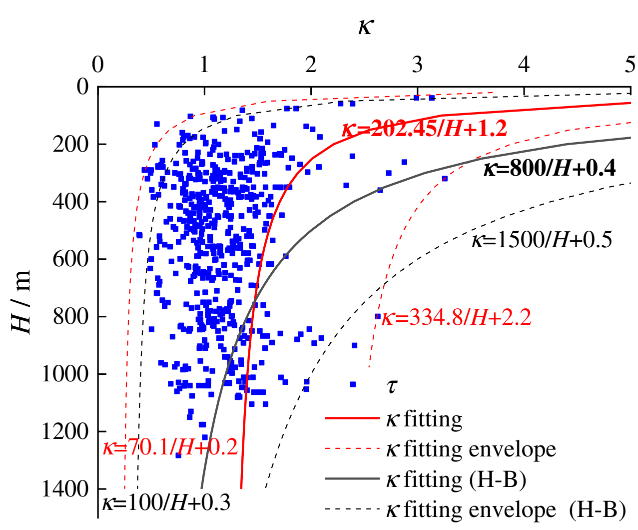

Fig. 7 Relationship between side pressure ratio and burial depth

The cause of these differences may be that the description of Hoek-Brown curve is the stress distribution characteristics and laws worldwide, and its measured data came not only from the sedimentary rocks, but also included a mass of magmatite rocks and metamorphic rocks. On account of the influence of region, burial depth, tectonic movement, and rock's mechanics performance, very sharp differences are formed in the characteristics of in situ stress field. For coal mines, in addition to regional differences, coal and rock are mainly sedimentary. However, there is a great difference among the sedimentary rocks, magmatite rocks, and metamorphic rocks in physical and mechanical properties, especially in coal seams. Whether it is caused by physical or mechanical properties, it always differs visibly from rock strata. All kinds of geological structures are present in coal-bearing strata, such as faults, joints, folds, and collapse columns. They also affect the size and direction of stress to different degrees. Although the distribution characteristics and laws of in situ stress in China's coal mines are similar to Hoek-Brown's conclusions, every in situ stress field also has its own characteristics. For this reason, some results of other mining areas or industries cannot simply be compared and applied.

Relationship among the direction of maximum horizontal principal stress, trajectory of principal stress, and seismic belt in China

The direction distribution of the maximum horizontal principal stress in China's coal mines is shown in Fig. 8. Generally, the direction of maximum horizontal principal stress is approximately parallel or perpendicular to the trajectories of principal stress in China Continental Plate. Nevertheless, when the coalfield is located in or near a seismic belt, because of the pushing and restriction impact of the continental plate, the direction of maximum horizontal principal stress is badly affected within the region, generating great dissociation and randomness. The direction of tectonic stress field exists significant differences in different coal mines, and they have no apparent relationship with the trajectories of principal stress. Because the statistical stresses are concentrated in China's central eastern area, also called North China. Further analysis was performed for this region, as shown in Fig. 9.

The North China seismic belt consists of 4 seismic belts including Tanlu seismic belt, North China Plain seismic belt, Fenwei seismic belt, and Yinchuan-Hetao seismic belt. The eastern coalfields are affected by Tanlu seismic belt and the Low Yellow River seismic belt, and the direction of tectonic stress field differed visibly. In the Shandong coalfields, the direction of maximum horizontal principal stress is NEE, NNE, and SEE as the dominant. It is respectively NNW, SEE, and NNE (Huainan) and SEE (Huaibei) in Henan,

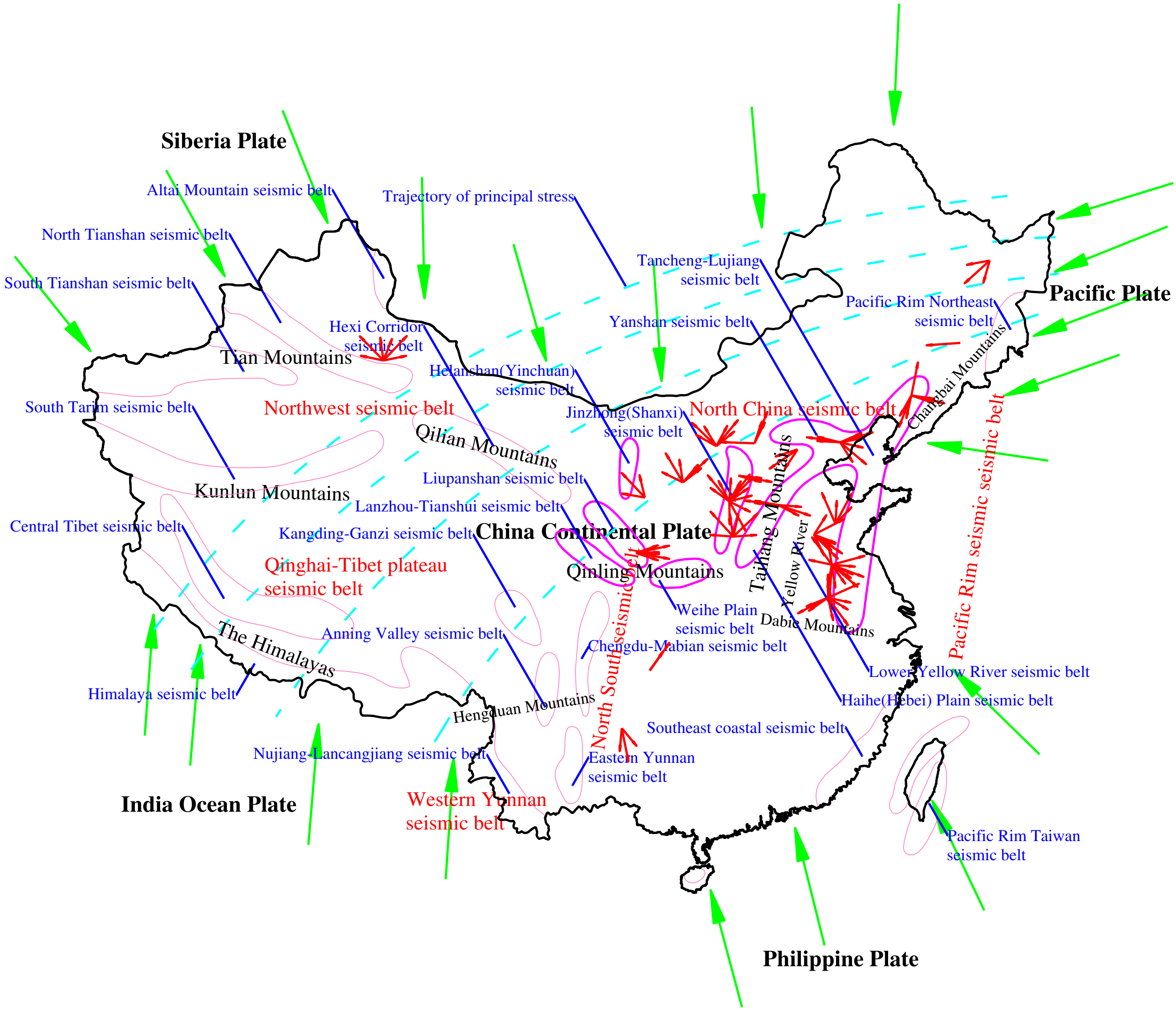

Fig. 8 Relationship among the direction of maximum horizontal principal stress, the trajectory of principal stress and seismic belt

Jiangsu, and Anhui, and there is no law to follow. Similarly, Shanxi coalfield is located mostly within the Jinzhong seismic belt, under the composite effect of Taihang Mountains, Haihe (Hebei) Plain seismic belt, and Yanshan seismic belt, and the environment of stress field is complex and changeable. The direction of maximum horizontal principal stress is NEE and NNW, SSE, NNE, NNE, and SEE in the Qinshui, Huoxi, Datong, Hedong, and Ningwu coalfields. Being in Yanshan seismic belt and Haihe Plain seismic belt, Hebei coalfield undergoes the effect of Taihang Mountains, Tanlu seismic belt and part of Low Yellow River seismic belt. And it is respectively SEE and NWW, SEE, and SWW in those coalfields: Hanxing, Kailuan, and Jingxi. When the coalfield, such as Ningdong coalfield and Huating coalfield, is affected by the single seismic belt, the direction of tectonic stress field is relatively regular and can form a small angle with the trend direction of seismic belt.

With the reduction and depletion of coal resources, the mining depth of China's coal mines will continue to increase, the high-stress work environment will continue to deteriorate, and the mines will experience severe underground pressures, difficult roadway maintenance, increased risk of rock burst, serious roof fall, and increased gas emission. In order to ensure the safe, efficient, and economic production, it is necessary to strengthen in situ stress measurement, and take corresponding support and preventive measures according to the actual stress state.

Conclusion

In this paper, 578 sets of in situ stress in China's coal mines were analyzed and some conclusions were drawn.

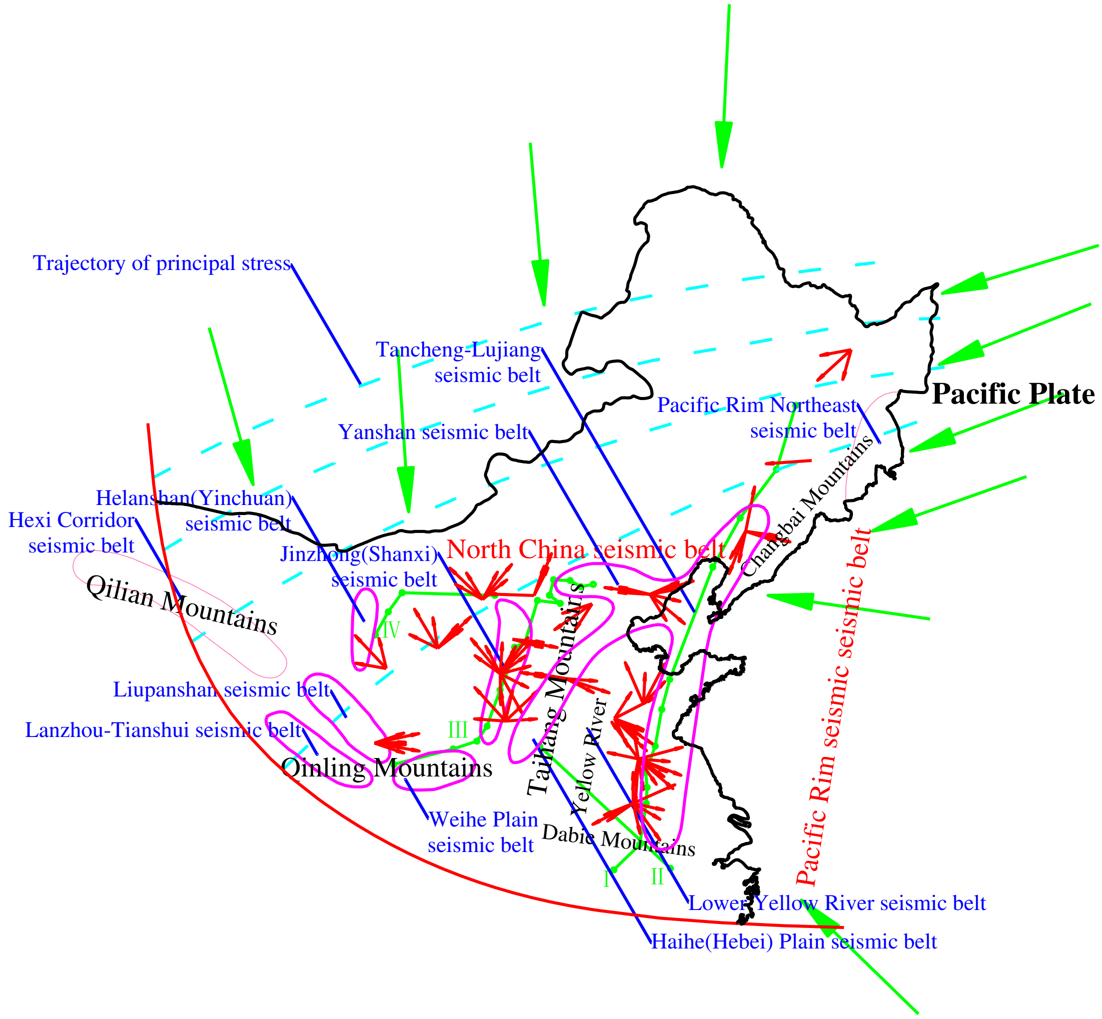

Fig. 9 Relationship among the direction of maximum horizontal principal stress, the trajectory of principal stress and the seismic belt in North China. I—Tanlu seismic belt; II—North China Plain seismic belt; III—Fenwei seismic belt; IV—Yinchuan-Hetao seismic belt

(1) A total of 87.72% stress fields in China's coal mines were found to rely mainly on horizontal stress, and tectonic stress was absolutely dominant, so they were treated as typical tectonic stress fields. About 64% stress fields belonged to the middle and high-stress zones, and the low- and ultrahigh-stress zones accounted for about 18%. Moreover, ultrahigh-stress zones mostly focused on in eastern coalfields.

(2) In general, the stress in coal mines increases with burial depth. The correlation of vertical principal stress is preferable, but the discreteness of horizontal principal stress is big due to the differences from the geological conditions of mining areas.

(3) The ratio of horizontal principal stress is concentrated within a ratio of 1.0~2.5, and it is affected by burial depth only slightly. The shear stress increases with burial depth. Its directivity is increasingly visible, which would bring about more severe damage extent to coal and rock.

(4) The side pressure coefficient mainly distributes in 0.9~2.0. It continually decreases with burial depth and finally tends to 1.32. Most side pressure ratios are in 0.5~1.6. As burial depth increases, its changing trend is almost in accordance with Hoek-Brown curve as a whole. When burial depth is less than 700~750 m, the horizontal principal stress is less pronounced than under real-world conditions. It occupies an absolute superiority in the stress field. The horizontal principal stress is greater, but it is always playing a dominant role in the stress field.

(5) The distribution characteristics and laws of in situ stress in China's coal mines are similar to Hoek-Brown's conclusion, but there are obvious differences about the measurement conditions of statistical data. So the distribution characteristics of stress field in coal mines should not simply follow some conclusions from other mining areas or industries.

(6) The in situ stress fields in China's coal mines are greatly affected by seismic belt. Without an effect of seismic belt, the direction of maximum horizontal principal stress is approximately parallel or perpendicular to the trajectories of principal stress in China Continental Plate. On the contrary, there is no well-marked relationship between the two. When the coalfield is affected by the single seismic belt, the direction of tectonic stress field, which can form a small angle with the trend direction of seismic belt, is relatively regular. When the coalfield tectonic stress field suffers from the composite effects of multiple seismic belt, its direction obviously changes and there is no law to follow.

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Compliance with ethical standards

Conflict of interest The authors declare that there is no conflict of interest.

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