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International Journal of Rock Mechanics & Mining Sciences 44 (2007) 1149–1171
International Journal of Rock Mechanics and Mining Sciences
www.elsevier.com/locate/ijrmms

A review of mining-induced seismicity in China

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Received 9 February 2007; accepted 21 May 2007
Available online 23 July 2007

Abstract

Active seismicity and rockbursting have been an emerging problem in Chinese mines. The distribution and characteristics of mining-induced seismicity in China, and its monitoring, mitigation, and research, are reviewed in this paper. Mining at depth and the activity of current tectonic stress field are the two major factors leading to rockburst hazards. Three critical depths, i.e., critical initiation depth, roof upper-bound depth, and floor lower-bound depth, have been identified based on hypocenter data of seismic events in coalmines. A strong correlation between rockbursts and gas outbursts in coalmines has also been established, and it is recommended to use this correlation for rockburst and gas outburst hazard assessment and warning interchangeably. We find that the key problems of rockburst hazard mitigation in China are the lack of mine seismicity-monitoring networks in most mines, and the need for improvement of the accuracy of the monitoring systems for mines that have been equipped with such systems. Because the demand for minerals resources is extremely high and the mining activities are progressing deeper and deeper, an increasing trend of mining-induced seismicity hazards in China may be anticipated for the near future. Mining-induced seismicities are hazards, but at the same time they have been found useful for studying geophysical problems in deep ground, particularly in the field of earthquake prediction. With the enforcement of relevant laws for the mining industry and the continuous effort to study rockburst problems using rock mechanics and geophysics principles and methods, it is believed that new approaches for rockburst hazard control and mitigation can be developed.

Keywords: Mining-induced seismicity; Rockbursts; Temporal and spatia distribution; Characteristic focal depths; Unusual methane gas emission; Hazards; Monitoring and research

1. Introduction

Excavation of large volumes of rocks at depth and the resulting stress redistribution can cause fracture initiation, propagation, and rock mass movement along pre-existing fracture planes. This process is usually accompanied by the generation of seismic waves known as mining-induced seismicity, which have been noticed in underground mining and civil tunneling projects worldwide. Hence, mining-induced seismicity can be defined as the rock mass response to deformation and failure of underground structures, including the rock mass itself. Mining-induced seismic events, which correspond to the sudden release of elastic strain energy in the rock mass, include ground movement caused by fault slip due to the interaction of tectonic stresses and mining-induced stresses away from mine openings and those caused by the sudden failure of rock masses due to stress concentration in the mining area. Rockbursts (or coal bumps in coalmines) are particular cases of seismic events induced by mining activity that cause injury to persons, or damage to underground workings. As a result, all rockbursts are seismic events, but not all mining-induced seismic events are rockbursts.

Since the first report of seismicity at South Stanford coalmine in England in 1738 [1,2], mining-induced seismicity has been recorded and reported in many countries, for almost all underground works (mining, tunneling), and in different rock type (hard brittle rocks such as granite, soft rocks such as coals). Although the strength or released

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1365-1609/$ - see front matter
doi:10.1016/j.ijrmms.2007.06.002

energy of mining-induced seismic events is small as compared to that of natural earthquakes, this type of seismic activity occurs frequently, at shallow ground (up to a few km), and is closely related to engineering activities (tunneling and mining). Mining-induced seismicity may cause production losses in underground mines, damage to equipment, collapse of drifts and stopes, and in extreme cases, loss of life. It is regarded now as a human-activity induced engineering and geophysical hazard.

Mining-induced seismicity has been investigated for a long time in many countries with mining tradition. The mining-induced seismicity problems in some other countries have been addressed at several international conferences [3–5], in a few special volumes of scientific journals [6,7], and by some well-received papers and books [8–10]. In the present paper, we focus our discussion on the mining-induced seismicity in underground mines in China. According to available literature, mining-induced seismicity in China was first reported in 1933, at Shengli coalmine in Fushun City, Liaoning Province [1,2]. Since then, many seismic events have been witnessed and serious damage to rock masses and equipments as well as threat to mine safety has brought the attention of researchers and engineers to this problem. Many research works, from rockburst mechanism study to rockburst hazard control and mitigation, have been carried out, in mining and civil engineering, and in the fields of rock mechanics and geophysics.

Significant work on mining-induced seismicity research and development has been carried out in China in the last 40 years, but, due to language differences, most of the work was almost unknown or had limited exposure in the English language. Hence, the objective of this paper is to provide a compact review on the different aspects of mining-induced seismicity in China, with particular attention paid to seismic hazard distribution, damage to mine operation, risk to mine personnel, seismic monitoring systems, past and state-of-the-art of knowledge and experience of mining-induced seismicity and its control as well as prediction attempts. Since it is impractical to describe all aspects in reasonable depth in a review paper, only the most important works will be reviewed with emphasis on the distribution, hazard, and monitoring of mining-induced seismicity.

2. Distribution of mining-induced seismicity

2.1. Spatial distribution

Mining-induced seismicity and rockbursts have been reported at 102 coalmines and 20 metallic and resources mines [11]. A comprehensive, although not complete, list of mines with rockburst problems is presented in Table 1. About 83.6% of the seismic activities occur in coalmines and the disasters are more serious in coalmines than in others. Mines with rockburst activities are mostly located in the east part of China, from Heilongjiang Province in northeast to Yunnan Province in southwest, roughly in a domain with NE–SW orientation as shown in Fig. 1. The distribution of coalmine seismicity approximately overlaps the distribution of major coalmines. In general, a majority of deep mines have experienced rockburst problems and suffered seismic damage to various degrees.

The depth of rockburst hypocenter is closely related to mining stope locations and geological structures. Some events are close to active mining stopes while others, which are due to fault slip, may be far away from the active mining areas. The shallowest depth at which rockburst had been recorded is 200 m (Mentougou coalmine in Beijing) and the deepest is about 7000 m (Taiji coalmine, Beipiao, Liaoning Province). Based on the rockburst hypocenter data we collected at some coalmines, we have identified three characteristic depths, i.e., critical initiation depth, roof upper-bound depth, and floor lower-bound depth for rockburst events.

The critical initiation depth is the depth beyond which rockbursts will happen. Mining-induced seismicity and hazards do not occur at the early stage of mine development when the depth is shallow. They only appear when mining activities reach a certain depth. In general, the higher the uniaxial compressive strength of coal is, the deeper the critical initiation depth. We find that the following log–log relationship correlates well the coal strength and the critical initiation depth in coalmines, i.e.,

$$\log H = 0.894 \log \sigma_c + 1.602, \quad (r^2 = 0.896), \tag{1}$$

where H is the critical initiation depth in meter and σ_c is the uniaxial compressive strength of coal in MPa. The minimum value of σ_c for coal seam had been used to derive Eq. (1). The above correlation was obtained using data from 14 case histories, and additional datasets are needed to verify it further. A plot of the relationship between $\log H$ and $\log \sigma_c$ is presented in Fig. 2. The critical initiation depth increases as the coal strength increases. If the density (γ) of roof rock masses were considered in establishing the correlation between γH and σ_c, a better correlation would be expected. Unfortunately, complete roof rock mass density data cannot be collected from the literature to pursue such a correlation analysis.

It should be noted that there are always exceptional cases that do not follow the trend defined by Eq. (1). One exception is the critical initiation depth at Datong coalfield in Shanxi Province. Coal seams in Datong are located 200–300 m underground. The uniaxial compressive strength of coal at Xinzhouyao coalmine is about 38.5 MPa, and the Protodyakonov scale of hardness f is 3–4 [12]. According to Eq. (1), the critical initiation depth would be about 1000 m. However, for several mines in the coalfield, including Xinzhouyao coalmine, the first rockburst event was recorded at a mining depth of about 250 m. According to the earthquake monitoring data obtained in 1971 from the Seismology Network of China, six strong earthquakes ($M_s \geqslant 5.0$, the maximum one was $M_s = 6.5$) happened within 15 years in this region. As shown in Fig. 3, the occurrence time of initial rockbursts correlated

Table 1
List of mines with mining-induced seismicity in China

No.	Province	Bureau/region/city	Mine	Time when seismic problem initiated	Initiation depth (m)	Max. magnitude $(M_L)_{max}$	Occurrence time of $(M_L)_{max}$
1	Heilongjiang	Hegang	Nanshan coalmine	1981.3	347	3.7	2001.2.1
2	Heilongjiang	Hegang	Fuli coalmine	1980s	400		
3	Heilongjiang	Hegang	Zhenxing coalmine	1998.6	400		
4	Heilongjiang	Shuangyashan	Gangdong coalmine	1974.1		2.3	
5	Heilongjiang	Jixi	Didao coalmine	1983.9			
6	Jilin	Shulang	Yingcheng coalmine	1962.1			
7	Jilin	Liaoyuan	Xian coalmine	1954.1	340		
8	Jilin	Liaoyuan	Taixin coalmine	1955			
9	Jilin	Tonghua	Tiechang coalmine	Unknown			
10	Liaoning	Fushun	Shengli coalmine	1933.1	300	2.8	1978.9.21
11	Liaoning	Fushun	Laohutai coalmine	1955.1	300	3.7	2002.1.26
12	Liaoning	Fushun	Longfeng coalmine	1975.1	300	2.5	1981.2.16
13	Liaoning	Fushun	Hongtuoshan copper mine	1976			
14	Liaoning	Fuxin	Gaode coalmine	1987.1			
15	Liaoning	Fuxin	Wulong coalmine	1959.1		3.8	2004.6.16
16	Liaoning	Fuxin	Dongliang coalmine	1984			
17	Liaoning	Beipiao	Taiji coalmine	1970.5	550	4.3	1977.4.28
18	Liaoning	Beipiao	Guanshan coalmine	1986			
19	Liaoning	Shenyang	Benxi Niuxintai coalmine	1972.9			
20	Liaoning	Shenyang	Benxi Caitun coalmine	2004.3		2.8	2004.4.13
21	Liaoning	Jianchang county	Binggou coalmine	Before 1980			
22	Beijing	Beijing	Mentougou coalmine	1947.5	200	4.2	1994.5.19
23	Beijing	Beijing	Chengzi coalmine	1961.1	330	3.4	
24	Beijing	Beijing	Fangshan coalmine	1958.12	520	3	1997.2.18
25	Beijing	Beijing	Changgouyu coalmine	1970.1			
26	Beijing	Beijing	Datai coalmine	1961.1	460		
27	Beijing	Beijing	Muchengjian coalmine	1970.1			
28	Hebei	Kailuan	Tangshan coalmine	1964.6	580		
29	Hebei	Cixian	Guangtai coalmine	Unknown			
30	Shanxi	Datong	Jinhuagong coalmine	1972.03		2.1	
31	Shanxi	Datong	Baidong coalmine			2.7	1983.9
32	Shanxi	Datong	Tongjialiang coalmine	1984	240		
33	Shanxi	Datong	Xinzhouyao coalmine	1981.1	250		
34	Shanxi	Datong	Meiyukou coalmine	1972.1	250		
35	Shanxi	Datong	Yongdingzhuang coalmine	1962.6	250		
36	Gansu	Pingliang	Huating coalmine	Early 21century		3.3	
37	Shandong	Zaozhuang	Taozhuang coalmine	1976.1	450	3.6	1982.1.7
38	Shandong	Zaozhuang	Bayi coalmine	1976.1	400		
39	Shandong	Zaozhuang	Chaili coalmine	Unknown			
40	Shandong	Xinwen	Huafeng coalmine	1991.1	710		
41	Shandong	Xinwen	Sunchun coalmine	1994.5	720		
42	Shandong	Xinwen	Zhangzhuan coalmine	1990.3	509		
43	Shandong	Xinwen	Panxi coalmine	1990s			
44	Shandong	Yankuang	Dongtan coalmine	2001.6			
45	Shandong	Yankuang	Baodian coalmine	2004			
46	Shandong	Weishanhu	#2 coalmine	Unknown			
47	Shandong	Zaozhuang	Shunyuan gypsum mine	Early 21 century		3.6	2002.5.20
48	Henan	Yima	Qianqiu coalmine	1988.1			
49	Henan	Hebi	Wumei coalmine	Unknown			
50	Henan	Pingdingshan	Shier coalmine	Unknown			
51	Jiangsu	Xuzhou	Quantai coalmine	1991.7	590		
52	Jiangsu	Xuzhou	Sanhejian coalmine	1991.5	545	3.4	2003.5.8
53	Jiangsu	Xuzhou	Qishan coalmine	1997.5			
54	Jiangsu	Xuzhou	Zhangxiaolou coalmine	1994.12	1025		
55	Jiangsu	Xuzhou	Zhangji coalmine	1994.8	575		
56	Jiangsu	Datun	Yaoqiao coalmine	1993.4	610		
57	Jiangsu	Datun	Kongzhuang coalmine	1997.2	550		

Table 1 (*continued*)

No.	Province	Bureau/region/city	Mine	Time when seismic problem initiated	Initiation depth (m)	Max. magnitude $(M_L)_{max}$	Occurrence time of $(M_L)_{max}$
58	Sichuan	Mianyang Beichuan	Leigu coalmine	1981.3			
59	Sichuan		Wuyi coalmine	1980.12			
60	Sichuan	Mianzhu	Tianchi coalmine	1959.1	240		
61	Sichuan	Leshan	Weixi salt mine	1970.9		4.2	1979.8.15
62	Sichuan	Zigong	Salt mine	1985.3		4.6	1985.3.29
63	Sichuan	South Bureau	Louguanshan # 4 well	1989		4.3	1994.4.15
64	Sichuan	Shizhu	Chayuan coalmine	1987.7		4.3	1987.7.2
65	Chongqing	Nantong	Yanshitai coalmine	1979.8	240		
66	Chongqing	Nantong	Nantong coalmine	1962.1			
67	Jiangxi	Xinyu	Huagushan coalmine	1984.9			
68	Jiangxi	Gaoan	Bajing coalmine	1996.7	460		
69	Jiangxi		Tungsten ore	Unknown			
70	Guizhou	Liuzhi	Huachu coalmine	1977		4.1	1982.3.20
71	Guizhou	Yingpan, Liuzhi	Sijiaotian coalmine	1985.1		2.7	1985.1.21
72	Guizhou	Yingpan, Liuzhi	Liuzhi coalmine	1985.1		3.6	1991.7.9
73	Guizhou	Yingpan, Liuzhi	Dizong coalmine	1985.1		2.7	1985.1.21
74	Guizhou	Yingpan, Liuzhi	Bingshuijing coalmine	1985.1		3.6	1991.7.9
75	Guizhou	Yingpan, Liuzhi	Dayong coalmine	1985.1		2.7	1985.1.21
76	Guizhou	Lindong	Xifeng Nanshan coalmine	1991.4		3.1	1991.4.6
77	Guizhou	Panjiang	Shanjiaocun coalmine	1991.12		3.1	1997.12.5
78	Guizhou	Panjiang	Yueliangtian coalmine	1991.12		3.1	1997.12.5
79	Guizhou	Shiucheng	Dahebian coalmine	1985.7		2.8	1985.7.9
80	Guizhou	Kaiyang	Kaiyang phosphorus mine	1990.10		2.2	1990.10.23
81	Guizhou	Zunyi	Manganese mine	Unknown			
82	Hunan	Xifenglun	Meitanba coalmine	1985.11		2.8	1991.4.23
83	Hunan	Lowde	Enkou coalmine	1974		2.9	1976.1.8
84	Hunan	Lowde	Doulishan coalmine	1980		2.5	1985.3.4
85	Hunan	Lowde	Qiaotouhe coalmine	1973		2.2	1974.5.31
86	Hunan	Shaoyang	Shixiajiang coalmine	1991.12		1.6	1991.12
87	Hunan	Shaoyang	Xindong coalmine	1985.2		3.0	1994.11.20
88	Hunan	Shaoyang	Niumasi coalmine	1980s		3.2	1997.9.4
89	Hunan	Shaoyang	Dahuatang coalmine	1980s		2.7	1997.12.4
90	Hunan	Tongling	Dongguashan copper mine	1993.			
91	Hunan	Lianyuan	Qingshan pyrite mine	1996.7		2.6	1996.7.1
92	Hunan	Lianyuan	Qixingjiezhen coalmine	1990s		3.1	1996.3.28
93	Hunan	Chenzhou	Xujiadong 711 uranium mine	Unknown		3.4	1998.3.12
94	Hunan	Huayuan	South manganese mine	1995.5			
95	Hunan	Xiangtan	Niwan gypsum mine	2003.1		2.8	2003.1.17
96	Hunan	Taojiang	Manganese mine	Unknown			
97	Hunan	Hengnan	Shuikoushan lead-zinc mine	Unknown		2.0	
98	Hubei	Yichang	Phosphorus mine	Unknown			
99	Hubei	Zigui, Yichang	Yanguan coalmine	1987		2.5	1988.5.14
100	Hubei	Jiupanshan, Yichang	Fengdouyan, Jiupanshan, Qishuping, Beituo coalmines	1987			
101	Hubei	Zigui, Yichang	Huayazi coalmine	1973.3		2.8	1973.3
102	Hubei	Zigui, Yichang	Huaibashi coalmine	1961		3.6	1972.3.13
103	Hubei	Changyang, Yichang	Yangmuxi coalmine	1985.7			
104	Hubei	Yichang	Songyi coalmine	1963			
105	Hubei	Yichang	Wacang, Shimacao, Chenjiapo coalmines	1971		3.8	1971.6.17
106	Guangxi	Dachangjingtian	Gaofeng metalliferous mine	1993.3			
107	Guangxi	Dachangjingtian	Tongkeng metalliferous mine	1990s			
108	Yunnan	Dounan	Manganese mine	Unknown			
109	Yunnan	Heqing	Manganese mine	Unknown			

Note: M_L is the Richard magnitude, also called the local magnitude. In this study, the surface wave magnitude, M_S, is also used to describe the magnitude of an earthquake. The relationship between these two magnitudes is $M_S = 1.13M_L - 1.08$.

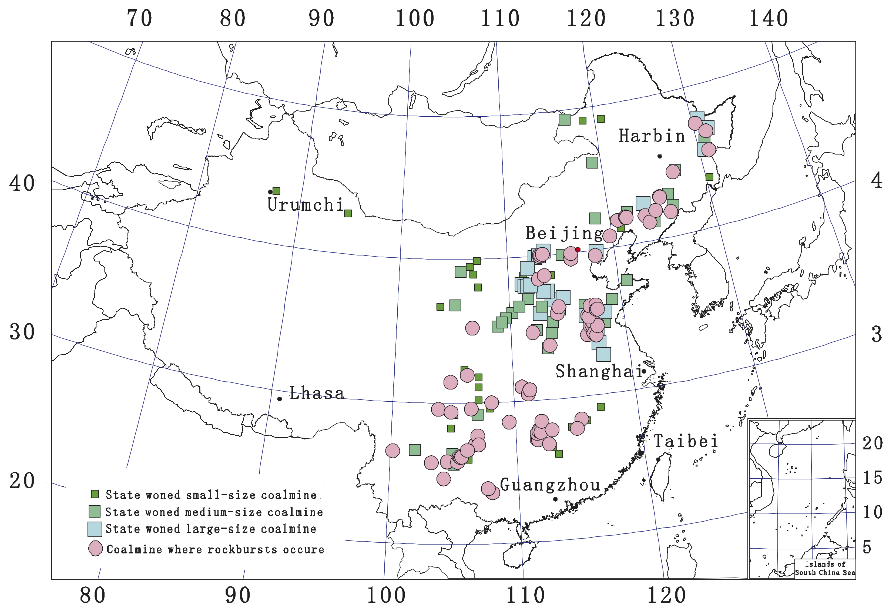

Fig. 1. Distribution of state-owned coalmines and mining-induced seismicity in China. Metallic mines and other mines as well as non-state-owned coalmines are not illustrated in the figure. (this map was based on Mapsis2.2 of Chinese Seismological Bureau).

well with that of the strong earthquakes. It is reckoned that the initiation depth is affected by the local tectonic stress field (maximum principal stress). Another reason is that the roof rock masses are very stiff, which can lead to higher stress concentration in the rock masses.

Another exception is identified at Quantai coalmine in Xuzhou, Jiangsu Province. The uniaxial compressive strength of coal at the mine site is 10 MPa, and the Protodyakonov scale of hardness f is 1. According to Eq. (1), the critical initiation depth would be about 300 m but the actual value is 590 m, almost twice the predicted value. One explanation is that coals at the mine are soft, and soft rocks are considered as rockburst free ground if the stress level is not high [13]. When mining activities reached 600 m, the ground stress increased substantially, affecting the mechanical behavior of the rock mass.

Since it is based on a limited number of case histories, we think that the regression line in Fig. 2 represents the approximate trend linking the critical initiation depth and coal strength. Two possible reasons can lead a data point deviates from the regression line. Points which lie above the regression line (such as the Quantai coalmine) indicate rock masses with no or weak rockburst tendency under moderate stress conditions. Severe rockburst will happen only when the ground stress is high, or the mining level is deep. For points below the regression line (like Datong coalmine), it is an indication that tectonic stress activity (or mining-induced stress) is high, which can lead to a shallow initiation depth. In other words, the initiation depth of rockburst is in fact a reflection of the relationship between rock stress magnitude and rock strength because in most cases the rock stress magnitude and overburden depth is closely related. For those cases that do not follow Eq. (1), it is suspected that the relative stiffness and strength of the

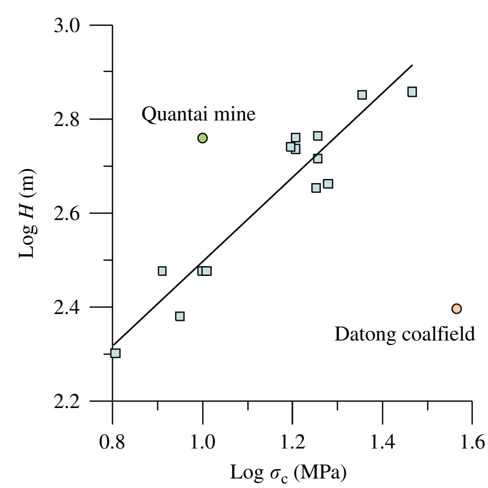

Fig. 2. Relationship between the critical initiation depth and the uniaxial compressive strength of coal.

coal body is different from the surrounding rock mass, or the local tectonic stress activity is high. If a stress or strength adjustment could be made to these outlying points, it is reckoned that they would approach the average regression line. Further investigation is needed to prove this observation/hypothesis.

The second characteristic depth is the roof upper-bound depth above mined stopes. Fractures exist in the roof rock mass above the mined areas and some major ones may even extend to the ground surface. However, mining-induced seismic events only happen below certain depth so that there exits an upper bound of the critical depth. Accurate seismic event source location work carried out at Laohutai mine (Fig. 4) [14], Taozhuan mine (Fig. 5) [15], and

Sanghejian mine (Lu and Li, 2005, personal communication) indicates that the upper-bound of the critical depth at these three mines is about 400–500 m.

An explanation of the roof upper-bound depth is given by the authors of this paper using a bending model of a thick plate or beam. The rock plate above the mined area will bend under gravity load. A neutral surface exists in a bending plate. The depth of the neutral surface is given by $H_c = H/(1+\sqrt{E_c/E_t})$, where H is the total thickness of the building beam, and E_c and E_t are the Young's moduli in the compression and tension zones, respectively. The rock mass below the neutral surface of the plate is in tension and above the neutral surface the rock mass is in compression. Since the tensile strength of the rock mass is small, the plate bending can introduce tensile fracturing of the lower portion of the plate, releasing the stored elastic energy and generating seismic waves. The compressive strength of the rock mass is high and the rock mass failure is delayed above the neutral surface. Even if the rock mass eventually can fail, the stored high elastic energy has been released due to the failure of the rock mass below the neutral surface. As a result, no rockburst or larger seismic activity will happen above the neutral surface and the neutral surface defines the upper bound of the critical depth.

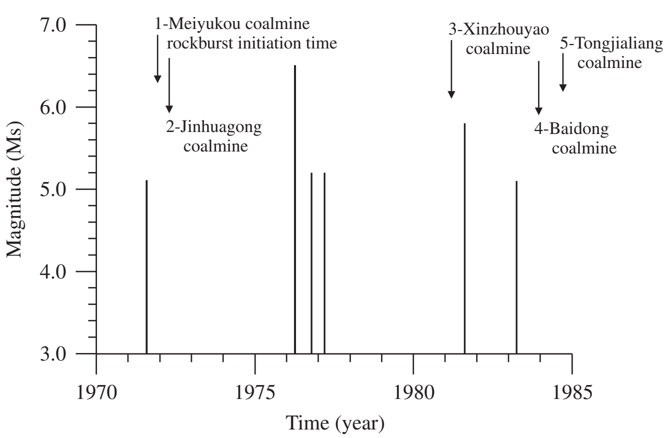

Fig. 3. Earthquake M–t distribution in a 150 km range at Datong coalfield.

Another explanation for the existence of the upper bound of the critical depth is based on the concept of the ratio of σ_c (UCS) to maximum far-field stress (σ_1). The average UCS of the roof rock mass (shale) at Laohutai coalmine is 39 MPa. According to Andersson et al. [16], for $\sigma_1/\sigma_c > 0.4$, there will be sizable seismic events ($M_L > 1$) as the rock mass is deformed. This is translated into a maximum far-field stress of about 15.6 MPa. At the mine site, the horizontal in situ stress is about twice the vertical component. Therefore, the vertical stress is equal to 7.8 MPa. The onset of seismic activity with a local magnitude greater than 1.0 would be at a depth of about 400 m (assuming an average density of the overburden as 2.0 t/m^3), which is in good agreement with the field monitoring data (see Table 1).

The third characteristic depth is the floor lower-bound depth below mined stopes or coal seams. The floor deforms and fractures when ore bodies are mined out. When the released energy is large enough, rockburst events can be generated below the active mining level. However, it seems that there exists a lower-bound depth for seismic activities in a mine. This lower-bound depth of mining-induced seismicity is usually within 1000 m below the active mining level but can be deeper if there are faults near by. For example, the floor lower-bound depth at Laohutai coalmine is about 3000 m (current mining depth is about 910 m). At Taiji coalmine in Beipiao, Liaoning Province, where recent tectonic stress activity is high, the floor lower-bound depth is about 6000 m. An illustration of these three critical depths is presented in Fig. 6.

The number of seismic events recorded within the orebody (mining area) is very low compared to the total number of seismic events recorded over the whole mine. This is evident from data obtained at two mine sites where extensive seismic monitoring programs were conducted. Only 3.35% of seismic events with $M_L \geqslant 0$ were found to be located in the orebody from 1999 to 2004 at Laohutai

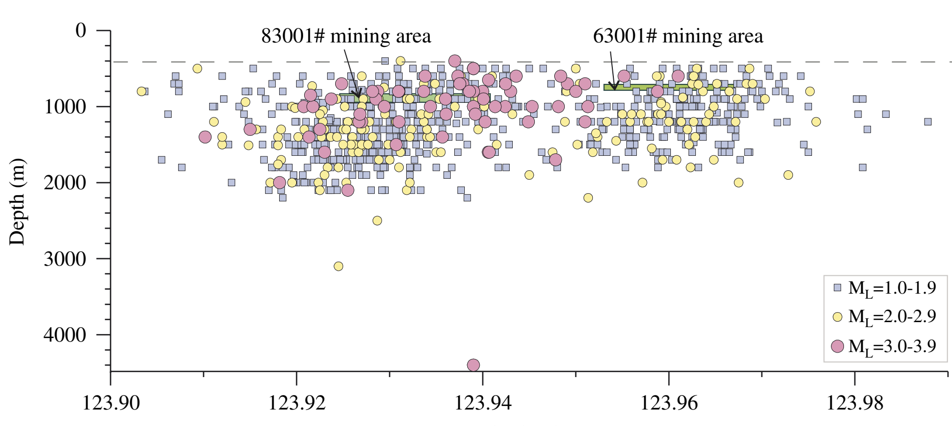

Fig. 4. Seismic event source location distribution (from July, 2003 to June, 2004) at Laohutai coalmine, Fushun, Liaoning Province.

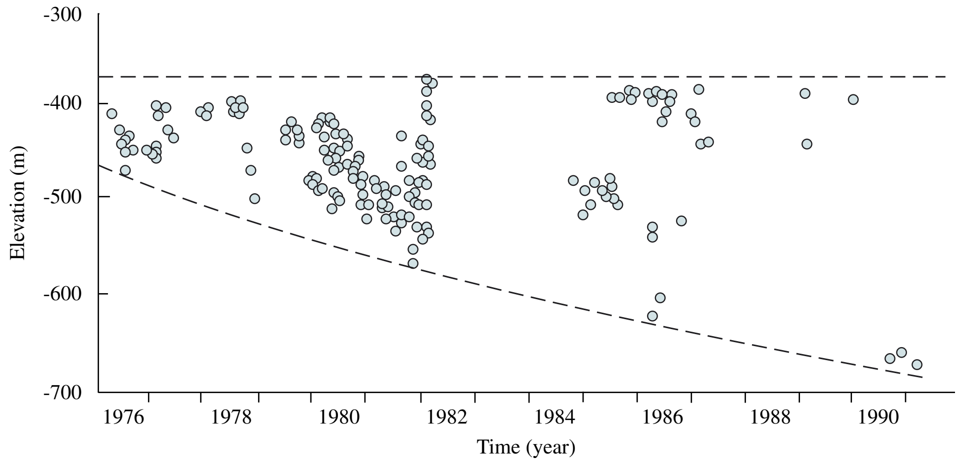

Fig. 5. Seismic event source location distribution (from July, 2003 to June, 2004) at Taozhuang coalmine, Shandong Province. The elevation of the ground surface is between 51 and 100 m.

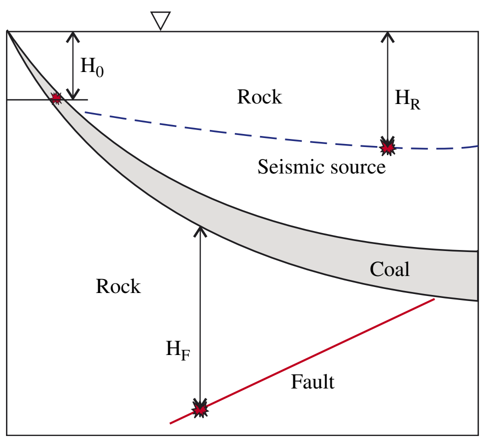

Fig. 6. Illustration of the critical depths of coalmine rockbursts. H_0—initiation depth; H_R—roof upper-bound depth; H_F—floor lower-bound depth.

coalmine. At Mentougou coalmine, about 0.5% of seismic events with $M_L \geqslant 1.0$ were found to be located in the orebody from 1987 to 1989. A rockburst index, defined as the number of seismic events observed within the mining area per million ton ore, had been used by some researchers for rockburst risk assessment [17]. Due to the lack of statistics representation, the index does not represent the overall seismic activities in a mine so that the application of such an index for rockburst hazard assessment and control is not recommended.

Besides coalmines, rockbursts have been reported in metalliferous mines at depth greater than 1000 m in Hunan, Yunnan, Guangxi, Guizhou, and Liaoning Provinces, salt mines in Sichuan Province, and gypsum mines in Shandong Province. Current mining depth at Hongtuoshan copper mine in Liaoning Province is about 1400 m. It is the deepest base metal mine and its rockburst problem is also the most severe one in all metalliferous mines in China. Zigong salt mine in Sichuan Province, which utilizes water injection mining method to mine salt from deep ground, held the record of the highest intensity ($M_L = 4.6$) of any mining-induced seismic events in China. In addition, seismic activities due to rock caving-in are most active at some gypsum mines in Zaozhuang city, Shandong Province.

Mining-induced seismicity is not contained in mines, or in a specific rock type. It can happen in almost any underground excavation and in any rock type. For example, rockbursts have been reported during the underground excavation of Ertan, Tianshengqiao 2, Laxiwa, Pubugou, and Taipingyi hydropower stations in hard rocks. On December 12, 1990, two large rockburst events happened during the excavation of the number 2 intake tunnel at the Tianshengqiao 2 site, resulting in a fall of ground of 300 m^3 [18]. When the overburden depth was less than 150 m, no seismic activity was observed during the tunnel excavation. The rock mass was slightly fractured at a depth range of 150–200 m. When the tunnel overburden depth reached 200–600 m, moderate to strong rockbursts were observed. Severe rockbursts were recorded at tunnel sections where the overburden depth reached over 600 m. During the excavation of the intake tunnel at Taipingyi hydropower station, the fall of ground that resulted from a large rockburst was 200 m^3 [18]. Similar rockburst problems have been encountered during the construction of Erlangshan tunnel of the Chengdu-Lasa highway. More than 200 rockburst events have been recorded since June 1996 [19].

2.2. Temporal distribution

As was stated before, the first mining-induced rockburst in China was reported in 1933, at Shengli coalmine in Fushun, Liaoning Province, when the mining depth reached about 300 m. As of today, the number of mines that have rockburst hazard problem has reached 122, 102 of them in coalmines and 20 in other types of mines (Table 1). Fig. 7 presents the evolution of the accumulated number of mines with rockburst hazard problem, showing a trend of exponential increase over time. It is believed that the increase of rockburst hazard is closely related to the pace of natural resource development and the gradual increase of mining depth. Further increase of mining-induced seismic activities is expected as mining progresses deeper. Additional discussion on future trend of rockburst problems is presented in Section 6.

2.3. Intensity and frequency

In total, 27 mines (22 in coalmines, three in salt mines, one in a uranium mine, and one in a gypsum mine) have experienced rockburst with magnitude $M_L \geqslant 3.0$. The mines with the highest event magnitudes ($M_L \geqslant 4.0$) are the salt mine in Zigong ($M_L = 4.6$, ore body depth 800–1800 m), Taiji coalmine ($M_L = 4.3$), Chayuan coalmine ($M_L = 4.3$), Mentougou coalmine ($M_L = 4.2$), and Huachu coalmine ($M_L = 4.1$). The largest mining-induced seismic event ($M_L = 4.6$) occurred on March 29, 1985, at Zigong salt mine in Sichuan Province. The intensity at the epicenter was VII (out of a total scale of 12) and the ground shaking was believed to be caused by water injection in the salt mining process [20,21].

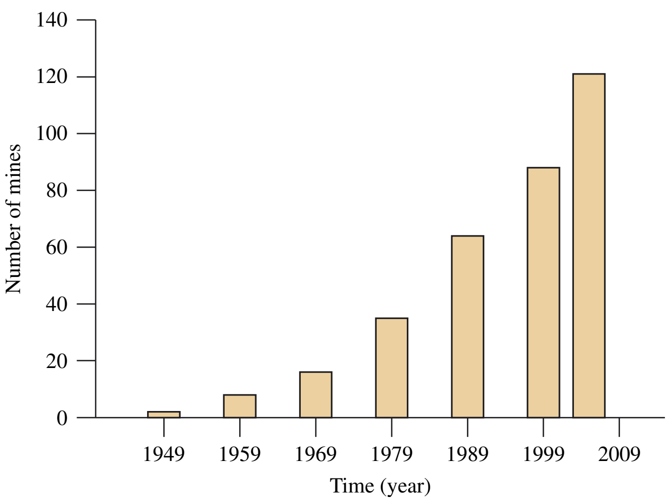

Fig. 7. Accumulated number of mines in China with rockburst hazard.

The $M_L = 4.3$ rockburst recorded on April 28, 1977 at Taiji coalmine in Beipiao, Liaoning Province is by far the largest seismic event in coalmines in China. As can be seen from Table 2, 2152 seismic events were recorded from 1971 to 1995 at the Taiji mine site and the mining-induced seismicity was believed to be affected by the tectonic stress activity [22–24]. Currently, there is no mining activity at the mine site and the seismic activity has been reduced to a very low level.

The frequency of seismic activities at Mentougou coalmine in Beijing was the highest in China. Before the mine was closed in July, 2000, a total of 110,913 seismic events with M_L magnitude greater than 1.0 had been recorded from 1980 to 2000 (Fig. 8), with an average of 5388 events/year (Zhang et al., 2004, personal communication). The seismic activity peaked in 1992 and gradually decreased afterwards. The mine seismicity is believed to be related to regional seismic activity which is affected by the tectonic stress field in the region [25,26].

A total of 92,630 mine seismic events ($M_L \geqslant 0$) have been recorded over the last 37 years (from 1968 to 2005) at Fushun coalfield in Liaoning Province. The highest seismic activity was observed in 2001 and 7222 events ($M_L \geqslant 0$) were recorded (Fig. 9). The maximum magnitude of the seismic events increased over time and strong rockburst events with $M_L \geqslant 3.0$ started to appear in 1990. Through July 30, 2005, 84 strong rockburst events ($M_L \geqslant 3.0$) have been reported at the coalfield. The largest rockburst, with $M_L \geqslant 3.7$, occurred in January 26, 2002. The seismic activity at Fushun coalmine is the highest, in terms of

Table 2
Statistics of mining-induced seismicity at Taiji coalmine from 1971 to 1995

Year	Number of events			Rockburst with damage	Max. magnitude (M_L)	Casualties	
	Total #	$M_L < 1.8$	$M_L \geqslant 1.8$			Death	Injury
1971–1982	219	42	177	42	4.3		17
1983	161	138	23	4	3.1		
1984	233	199	34	10	2.1		
1985	178	169	9	6	2.1		
1986	199	190	9	7	1.9		
1987	134	130	4	4	3.1		
1988	78	71	7	7	2.0		
1989	161	150	11	9	3.2		
1990	194	187	7	12	3.6		1
1991	128	122	6	18	3.2		
1992	116	111	5	18	2.0		
1993	93	89	4	9	1.8		
1994	226	215	11	30	3.2	7	7
1995.2	32	29	3	5	2.8		
Total	2152	1842	310	181		7	25

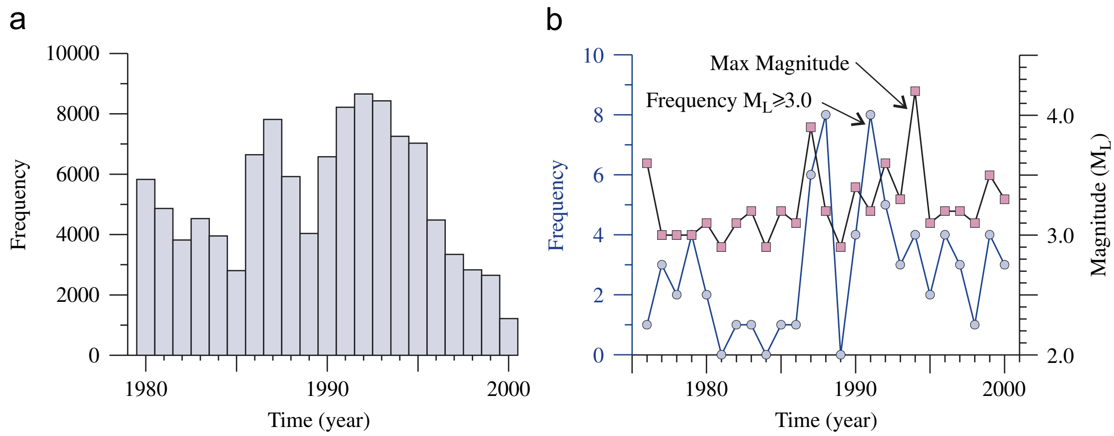

Fig. 8. Sequential distribution of mining-induced seismic events at Mentougou coalmine in Beijing: (a) events with $M_L \geqslant 1.0$; (b) events with $M_L \geqslant 3.0$ and the maximum event magnitudes.

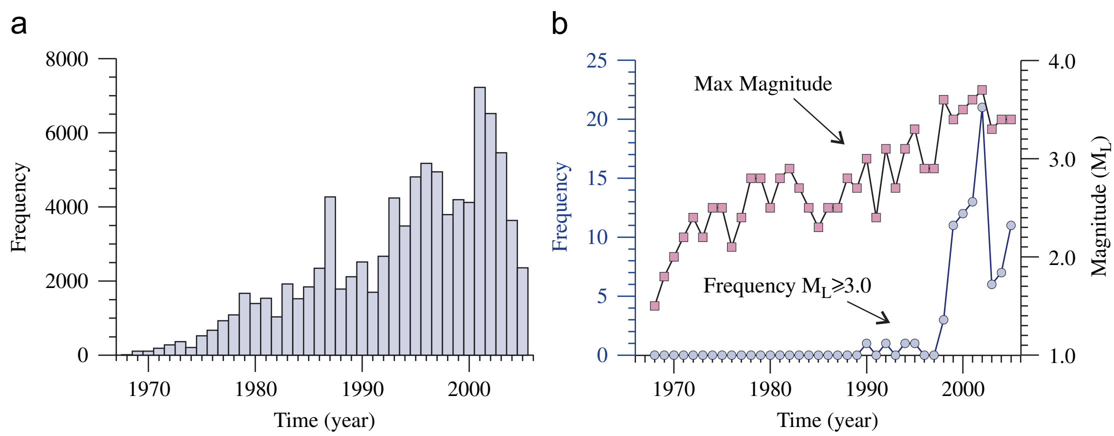

Fig. 9. Sequential distribution of mining-induced seismic events at Fushun coalmine field in Liaoning Province: (a) events with $M_L \geqslant 0.0$; (b) events with $M_L \geqslant 3.0$ and the maximum event magnitudes.

frequency, in all operating mines in China. The regional geological condition is relatively stable and no destructive natural earthquakes happened over the last 500 years. The current active mine seismicity is not related to the regional-scale earthquake activity [27].

Rockburst events started to appear at Wulong, Dongliang, Gaode coalmines (which belong to the Fuxin Coalmine Group), in 1959, 1984, 1987, respectively [28]. When the deep mining project initiated in 1997, seismic activities increased notably as shown in Fig. 10. In 2004 alone, 22 rockbursts with $M_L \geqslant 3.0$ happened and it was the most seismic active year at Fuxin coalfield. The largest recorded rockburst in this area happened at Wulong coalmine on June 16, 2004. Some researchers (Song and Wang, 2005, personal communication) consider that the occurrence of high rockburst activities in the coalmines in Fuxin city could be related to the active tectonic stress field. This is supported by good correlation between large rockbursts at Fuxin coalfield and natural earthquakes in the Northeastern region (Fig. 11). Fuxin coalfield is located on the west part of Lianing Province, and is one of the areas with active tectonic stress activities in the Northeastern region. This coalfield had been designated as a window to monitor change of regional tectonic stress activities for a long time. Other researchers believe that such a linkage of mine rockburst activities to regional tectonic stress activities could provide a method to predict the occurrence of natural earthquakes [29]. Further discussion on this topic is presented in Section 5.3.

Currently, the average mining depth at coalmines of Xinwen Group in Shandong Province is about 750 m, and three mines are now producing coals at a depth of 950–1000 m. Rockburst activities have appeared at four mines (Huanfeng, Sunchun, Zhangzhuan, Panxi, see also Table 1). The first rockburst was reported on January 14, 1991, at Huanfeng mine. Rockburst activities were most frequent at the −750 m level (overburden depth 850 m). About 30% of the rockbursts happened on the floor [30]. Twelve rockbursts with severe damage were recorded from 1992 to 2001 and the largest event registered $M_L \geqslant 2.5$ at Huanfeng mine. One unit of high frequency seismograph (DD-2) installed at Taian city had been designated for the

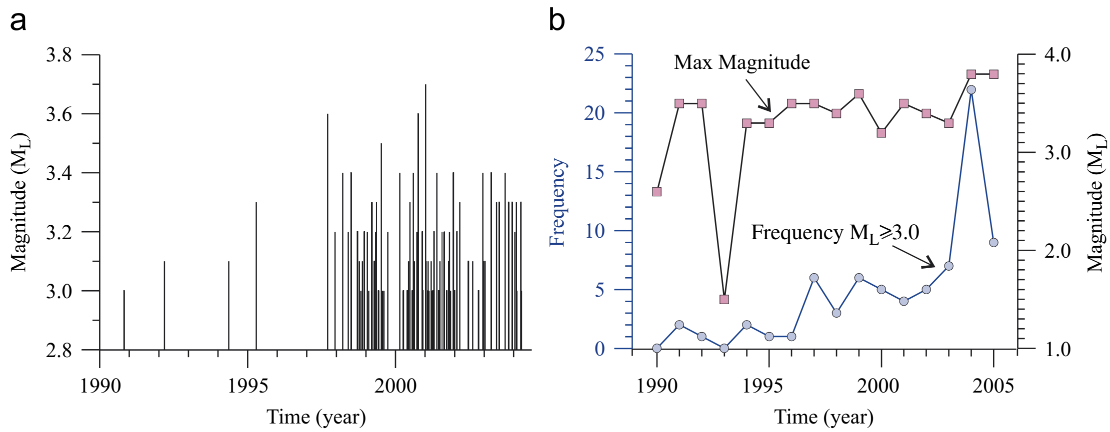

Fig. 10. Sequential distribution of mining-induced seismic events at Fuxin coalfield in Liaoning Province: (a) magnitude–time distribution; (b) events with $M_L \geqslant 3.0$ and the maximum event magnitudes.

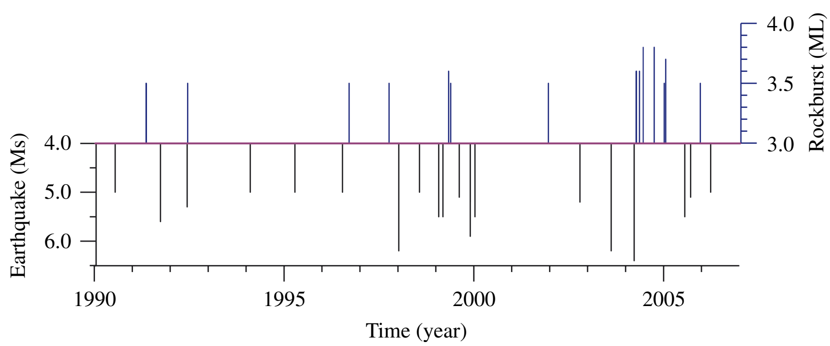

Fig. 11. Magnitude–time distribution of rockbursts ($M_L \geqslant 3.5$) at Fuxin coalfield and natural earthquakes ($M_S \geqslant 5.0$) in the Northeastern region from 1990 to 2006.

mine seismicity monitoring. The equipment can detect seismic events greater than $M_L = 0.1$. So far, 10,995 seismic events with $M_L \geqslant 0.5$ have been recorded at Huanfeng mine, among which about 1000 events are greater than $M_L = 1.0$ [31]. The mine seismicity at Taozhuang coalmine was also very active. Seismic monitoring program at the mine was initiated after the great Tangshan earthquake ($M_L = 7.8$), which obliterated the city of Tangshan and killed over 240,000 people in 1976. Over 10,000 seismic events were recorded at Taozhuang coalmine between 1976 and 1990. Seismic events with $M_L \geqslant 1.2$ totaled 1700 and the largest event was $M_L = 3.6$, which happened on January 7, 1982.

Mining-induced seismic activities in coalmines in central Hunan Province are primarily concentrated at Lowdi and Shaoyang coalfields. The event M-t distribution for all the coalmines in Hunan Province is presented in Fig. 12. A quiet period from 1978 to 1985 shows a good correlation of mine seismicity to the regional tectonic stress field because in the same period the regional seismic activities were calm as well [32].

At Liuzhi coalfield in Guizhou Province, small mining-induced seismic events started to appear in 1977. Extensive seismic activities were recorded from 1981 to 1982. Six

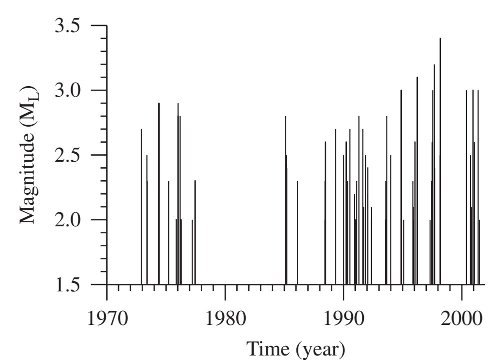

Fig. 12. Magnitude–time distribution for all mine seismic event with $M_L \geqslant 2.0$ in Hunan Province.

large rockbursts with $M_L \geqslant 3.0$ were recorded within a 40 day period from February 8 to March 20, 1982, and the largest was measured at $M_L = 4.1$ [33]. The statistics of the mining-induced seismic events at Hegang coalfield in Heilongjiang Province is presented in Table 3. 3029 seismic events with $M_L \geqslant 0$ were recorded from 1998 to 2003, with an average of 500 events/year. The largest rockburst ($M_L = 3.7$) was recorded at Nanshan mine on February

Table 3
Statistics of the seismic activities at Hegang coalfield in Heilongjiang Province

Year	Frequency				Total
	$M_L = 0$–0.9	$M_L = 1.0$–1.9	$M_L = 2.0$–2.9	$M_L = 3.0$–3.9	
1998	174	20	4	0	198
1999	247	55	13	1	316
2000	500	108	19	4	631
2001	386	49	10	3	448
2002	349	147	6	1	503
2003	368	534	25	4	933

1, 2001. Again, the seismic activity at Nanshan mine is believed to be related, to certain extent, to the activity of the regional tectonic stress field [34]. It should be noted that mining-induced seismicity can be correlated to many other factors such as rock mass conditions, mining technique, mining activity, or any other human activity, correlation to tectonic stress may be only suggested as a potential explanation, certainly not a firm conclusion. What had been demonstrated was a weak correlation of large rockbursts and earthquakes in the time sequence. Since earthquakes are influenced by the tectonic stress activity, the occurrences of some large rockburst events in mines may be influenced by the same activities that trigger earthquakes.

The Three Gorges Projects, which is now under construction, is the largest water conservation project in the world. Its hydropower plant is the world's biggest, with a generation capacity of 18.2 million kw. Due to the importance of the project, extensive geological investigation was carried out before the start of the dam construction. It was found that some minor earthquakes were observed in the periphery of the dam site. These ground-shaking events were previously investigated as geological structural earthquakes, often regarded as evidences of new fault movement. Recently, Hu et al. [35] pointed out that these minor tremors were, in fact, mining induced.

At mine sites where the seismic activities are high, the active mining depths are all below 700 m. Seismicity at some mines has periodic behavior, which is clearly related to the local natural seismic activity, suggesting that these mine seismic activities are affected by the tectonic stress field. It is obvious that mining depth and tectonic stress field are two major factors governing mine seismicity.

3. Characteristics of mining-induced seismicity hazards

3.1. Hazards to mine personnel, equipment, and production

On October 25, 1974, a rockburst at Chengzi coalmine in Beijing claimed 29 lives [36]. The event happened during the retrieve of pillars, and this was the rockburst event that caused the most casualties in China. On February 14, 1994, an $M_L = 2.5$ rockburst stroke Taiji coalmine in Liaoning Province, killing five miners and causing a production loss of 2.42 million Yuan [1]. From 1950 to 1999, rockbursts at Longfeng coalmine in Fushun had resulted in 48 deaths and the rockburst happened on February 22, 1978 claimed five lives [36]. The rockburst related casualty number at Laohutai coalmine in Fushun was sixty-seven from 1950 to 2003. From 1989, rockburst activities increased drastically at the mine site and in the last 15 years, 38 people have lost their lives due to violent rockbursts. Two large rockbursts, with the magnitude of $M_L = 2.7$ and 2.8, happened on January 6 and 12, 2001, respectively, resulting in four deaths and 28 injuries and major disruption to the production. The mining activity was stopped, 300 m long drifts severely damaged (Fig. 13), and about 200,000 tons of coal production was lost, leading to a direct loss of more than 100 million Yuan [37]. This was the single most costly rockburst that had happened in China. On April 18, 2002, a rockburst ($M_L = 2.6$) at Wulong coalmine in Fuxin killed eight miners (Song, 2005, personal communication). On January 7, 1982, a rockburst ($M_L = 3.2$) stroke Taozhuang coalmine in Shandong Province, resulting in five deaths, six injuries, and permanent loss of mine stopes (500,000 tons of high grade coal) [38]. From 1990 to 1999, mine rockbursts had killed 22 lives at Tianchi coalmine in Sichuan Province [39]. Block caving method was used from 1975 at Datong coalfield in Shanxi Province. On September 5, 1983, roof collapse at Baidong mine triggered ground movement. The energy released was equivalent to an $M_L = 2.7$ seismic event. Surface damage, in the form of subsidence, totaled an area of 10,000 m^2 and the economic loss was enormous [40].

Fig. 13. Damaged drift at 55,001 mining area at Laohutai coalmine.

Hongtuoshan copper mine in Fushun city started mine development in 1958. The first report of rockburst at the mine site dates back to 1976. The rockburst events observed at the depth of 437 m were characterized as rock ejection (to a distance of 2–3 m), accompanied with popping sounds. Rock ejection and pillar bursts were reported at the mining depth of 1037–1217 m. The intensity and frequency of popping sounds increased drastically at these mining levels. Pillar bursts happened in 10 mining areas, leading to sudden fall of roof of about 200–400 m^2, miner casualty and injury as well as loss of some stopes. Above the depth of 1200 m, pillar bursts were recorded only in areas where the stopes were large. At the depth below 1200 m, rockbursts were encountered even during drift development. Currently, the mining depth is below 1400 m and the rockburst hazard presents a severe threat to mine safety. Rockburst events usually cause severe damage to drifts over several dozens of meters and the generated seismic waves can be felt on the ground surface. The rockburst problem at Hongtuoshan mine tops in all hard rock mines in China [41,42].

The gypsum mines in Zhaozhuan city of Shandong Province occupies an area of 16.7 km^2. At 21:15, May 20 of 2002, a rockburst occurred due to large-scale roof falls. The magnitude of the rockburst was $M_L = 3.6$, determined by the monitoring network of the Seismology Bureau of Shandong Province. The fall of roof totaled 2.3 million tons. The roof failure was catastrophic and the mining stopes were filled with broken rocks. The center of the ground fall event was located at Shunyuan mine and several other ground falls were also encountered at other mines near by. High-pressure gas waves were generated by the large-scale roof failure. A mixture of gas and rock debris erupted from the shafts and this outbreak continued for about five minutes, forming several large rock piles around the shafts. Fortunately, 410 miners in all five mines avoided the danger because of the accurate warning of roof fall and prompt evacuation of mining crews. This was the fourth time that miner's lives had been saved in mine roof failure incidents in Zhaozhuan city, although the mine infrastructures were severely damaged [43].

3.2. Hazards to surface structures and environment

The number of mining-induced seismic events increases as mining activities progress deeper and large volumes of ores are mined out. Rockbursts with M_L magnitudes greater than 3.0 and 3.5 have been reported in 27 and 13 mines, respectively (see also Table 1). Some of the rockbursts not only endangered mine personnel, damaged underground equipments and infrastructures, but also caused damage to surface structures and environment. The impact of these hazards to society is substantial, especially to people living in the affected areas.

The $M_L = 4.3$ rockburst recorded on April 28, 1977 at Taiji coalmine was equivalent to a medium-size earthquake with an intensity of VII. A total of 1164 surface houses were damaged to various degrees, and twelve people were injured. The surface office building of Taiji coalmine was also damaged. On February 27, 1990, another large rockburst ($M_L = 3.6$) hit the same mine and some residential houses located at the epicenter were damaged [24]. The rockburst ($M_L = 4.2$) happened at Mentougou coalmine in Beijing, on May 19, 1994, caused damage to 5318 houses and a direct economic loss of at least 3 million Yuan. Dispute between local residents and the mine management was sparked and lasted for a long time [44]. Mentougou coalmine had been listed as one of the ten industrial hazards in Beijing in 1986 [45]. The mine was eventually closed in July of 2000. Six large rockbursts, measured at $M_L \geqslant 3.0$, occurred at Huachu mine (Liuzhi coalfield in Guizhou Province) from February 8 to March 20, 1982. The maximum event was measured at $M_L = 4.1$ and an intensity of VI. Three surface buildings were severely damaged and some infrastructures slightly damaged [33]. Surface residential houses were also damaged due to the rockburst ($M_L = 3.7$) that took place on February 1, 2001, at Nanshan coalmine in Heilongjiang Province [34].

Rockbursts with $M_L \geqslant 3.0$ happened frequently at Laohutai coalmine, causing fatigue damage to nearby surface structures. These repeated seismic events activated rock failure in empty stopes, which had been stable over seventy years. Sudden roof falls resulted, leading to surface subsidence in the mining camps (Fig. 14). A few faults were activated due to the horizontal movement of rock layers towards the stopes. Some surface buildings were damaged due to the fault movement (Fig. 15). Buildings parallel to the fault suffered tilt damage and those perpendicular to the fault were damaged in tension [46,47].

The ground fall rockburst at a gypsum mine in Zhaozhuan on May 20, 2002 caused severe surface subsidence. The surface subsidence area was about 144,700 m^2 and about 130,000 m^2 wheat field was lost almost instantly due to the ground fall [43].

3.3. Gas outburst

Gas outburst, the extreme of unusual gas emission, is a sudden ejection of gas from a coal body. Gas outbursts, characterized by the abrupt release of high density and large volumes of gases at certain locations in a mine, have

Fig. 14. Sudden roof failure leading the ground subsidence at Laohutai coalmine.

Fig. 15. Demolition of the apartment buildings damaged by rockbursts in Fushun City, Liaoning Province.

Table 4
Statistics of seismic events and high gas density events at Laohutai coalmine from 1997 to 2004

Elevation (m)	Total seismic event number (1)	No. of seismic events with unusual gas emission (2)	Ratio of unusual gas emission event to total seismic event (2)/(1) (%)
>−580	165	1	0.6
−630	224	13	5.8
−680	269	34	12.6
−730	135	10	7.4
−780	337	83	24.6
−830	87	40	46.0
Total	1217	181	14.9

Note: The surface elevation at the mine is 82 m.

been the cause of many disasters in underground coalmines. Twenty-nine rockbursts were recorded at Taiji coalmine from 1992 to 1997, and 11 of them accompanied with gas outbursts (Huang and Li, 2004, personal communication). It was noticed that (methane) gas content, defined as the methane gas percentage in the air, exceeded the safety limit (1%) over several times when rockbursts with $M_L \geqslant 3.0$ were encountered in mines at Hegang coalfield [34]. In recent years, coalmine disaster claimed lives of about 6000 miners a year in China, mostly in small operations run by local governments and businessmen. The majority of the incidents were due to methane gas explosion. At Sunjiawan coalmine in Fuxin city, where the mining depth is currently at 720 m, a huge gas explosion occurred on February 14, 2005, killing 214 miners working underground. According to the seismology network of Fuxin city, a rockburst ($M_L = 2.7$) event was recorded at 14:49 on the same day and the gas explosion happened fourteen minutes right after the rockburst event. The gas explosion itself was equivalent to a seismic event with $M_L = 0.6$. It is reckoned that the gas explosion was linked to the rockburst that released excessive gas in the mine (Song and Wang, 2005, personal communication). In most cases, the coalmine unusual gas emission, sometimes classified as gas outburst, was so quick and the density was so high that even sparks induced by rock movement could trigger a gas explosion.

On May 28, 1997, a gas outburst happened near a fault at Longfeng coalmine in Fushun city. High-density methane gas stored in the fault was released suddenly to the mining area. A massive gas explosion, caused by the sparks generated by the impact of rocks, claimed the lives of 69 miners.

Studies carried out at Laohutai coalmine on gas outburst demonstrated that a strong correlation between seismic activity and gas explosion disaster exists in deep mines with high gas content [48]. About 1217 seismic events were recorded at the mine site from July 1997 to September 2004, and 181 events (about 15% of the total events) were accompanied with high gas density well exceeding the safety limit (Table 4). Abnormal gas emissions varied with depth. There was almost no gas emission accompanying seismic events above the −580 m elevation. Below −630 m, systematic gas emission started to associate with rockburst activity. The percentage of the seismic events with unusual gas emission increased to 24.6% at the −780 m elevation and reached 46% at the −830 m level (Table 4). Thirty-one rockburst events were recorded from May 2003 to September 2004. In five instances, unusual gas emission was observed before rockbursts. Unusual gas emission was confirmed in nine and 17 cases, during and after rockburst, respectively. The ratios of unusual gas emission events before, during, and after rockburst to the total events were 16%, 29%, and 55%, respectively. Using event location data obtained by the microseismic monitoring system installed at the mine, we found that most of these events concentrated in the active 83001 mining area (currently the deepest mining area) or within 1500 m of the mined stopes. The maximum distance between the events was 2630 m.

Gas outburst is the biggest risk to coalmine safety. It is evident that when mining at depth, strong correlation between rockburst and gas outburst exists. However, unusual gas emission triggered by rockburst can only happen when several conditions are met. Firstly, there must be gas stored in the coal seam and the gas pressure is high. Secondly, there is space for gas to be released. Thirdly, there are fractures for gas to transport. When these conditions are met, any rockburst due to rock failure could trigger unusual gas emissions, increasing the chance of a gas explosion. Gas release is possible not only during and after rockburst, but also before rockburst because of the fracture propagation and coalescence right before the rock mass stress reaches to its peak strength. Unusual gas emission is not necessarily linked to gas explosion and poison to miners. Some preventive measures, such as installing automatic warning systems, providing good ventilation to the mine, avoiding high temperature and sparks, can prevent these accidents from happening. In general, gas outburst is one of the important areas that needs to be further studied to improve coalmine safety in China [48].

4. Rockburst monitoring

Seismic monitoring program was executed at some mines in China. Mine seismic monitoring has been proven as a useful tool to quantify mining-induced seismicities and has contributed valuable data to many studies on rockburst control and prevention. Mine seismic monitoring systems can be classified in two groups, i.e., homemade and imported systems. Homemade systems include DD-1, DD-2, 573, 768 analog seismographs, and JC-V100 and -V104 digital seismographs. A picture showing the JC-V104 triaxial velocity sensor is provided in Fig. 16. For the analog systems, the sensors have a frequency range of 1–20 Hz and the damping coefficient ranges from 0.45 to 0.5. For the digital systems, sensor frequency range is 1–20 Hz, the damping coefficient is 0.7, and the sampling rates are adjustable to either 50 or 100 Hz. Imported systems include SAK-SYLOK (frequency range 1–50 Hz), SAK-3 (frequency range 200–2500 Hz) seismic monitoring systems from Poland and the integrated Hyperion microseismic monitoring system (frequency range 1 Hz–10 kHz) from ESG (Engineering Seismology Group Inc.) in Canada. Most mines record seismic events with M_L magnitude above −1.

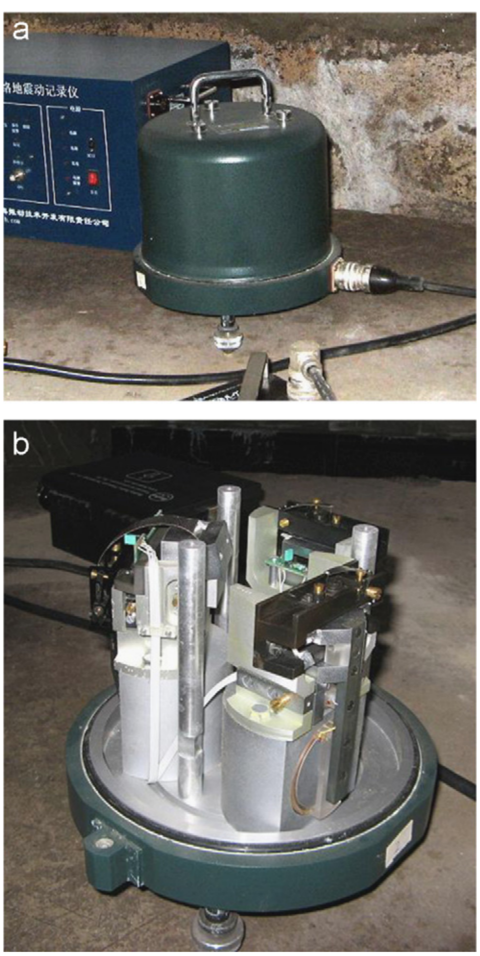

Fig. 16. Triaxial velocity sensor for the JC-V104 digital seismographer: (a) outside view; (b) internal components.

The first mine seismic monitoring system was established in 1959. Most mines depend on the regional seismology network to locate large mining-induced seismic events. For example, Huafeng coalmine in Shandong Province, currently mined at a depth of 950–1000 m, relies on the DD-2 seismography at Taian city to monitor mine seismicity. The lower magnitude limit of DD-2 is $M_L = -0.3$. Based on the monitoring conducted by the local seismic network in Taian city, 10,995 seismic events with $M_L \geqslant 0.5$ have been recorded at Huafeng mine in Shandong, among them about a thousand events have $M_L \geqslant 1.0$ [30]. Some mines have designated uniaxial sensors to monitor ground vibration and only a few mines have sensor arrays installed that are capable of event locating. At mines without seismic or microseismic monitoring system, rockburst studies are conducted by underground survey of damage.

The 8-channel SAK-SYLOK microseismic monitoring system, manufactured in Poland, was introduced into Chinese coalmines in 1984. The system was slightly modified to fit smaller drill holes and to enhance its mobility. Source locating task could be accomplished within 3–5 s and the accuracy of source location is ±100 m. Field test was conducted in 1988 using blasting events with known source locations to determine the source locating accuracy. The first arrival P-waves from eight sensors are used for event source locating. The SAK-SYLOK systems had been installed at Fangshan coalmine in Beijing, Longfeng coalmine in Fushun city, Datong coalfield in Shanxi Province, and Taozhuang coalmine in Shandong Province. ESG's digital microseismic monitoring system (Hyperion) was recently introduced to Fankou lead–zinc mine in Guangdong Province in 2004 [49]. The system installed at Fankou mine is the first microseismic monitoring system in Chinese metallic mines. It is a full waveform 16-bit resolution data acquisition system with a true monitoring frequency range of tens Hz to 5 kHz, with a sensor array covering a rock volume of 300 × 300 × 300 m. Compared to the SAK-SYLOK system, the Hyperion microseismic monitoring system can apply high frequency sensors to cover a smaller volume and hence provide a higher resolution of event location better than ±10 m. In 2004, another set of ESG's microseismic monitoring system was acquired by Northeastern University in Shenyang, China, and will be installed at a nearby mine for experimental purpose (Tang, 2004, personal communication).

Mentougou coalmine in Beijing was the first mine that had a seismic monitoring system installed. A uniaxial sensor system was installed in 1959 and non-continuous monitoring was conducted until 1964. High frequency triaxial sensor system, DD-1, was added to the mine after the great Tangshan earthquake in 1976. In 1984, an 8-channel Poland SAK-SYLOK system was installed along with another triaxial seismography system, with a seismic event locating accuracy about ± 100 m. A comparison study of DD-1 and SAK-SYLOK systems was carried out at the mine [50]. From 1987 to 1989, 18,070 seismic events whose magnitudes M_L were greater than 1.0 were recorded by the DD-1 system. During the same period, the SAK-SYLOK system recorded only 6848 events (3584 were source located), or about 37.9% of the events recorded by the DD-1 system [44,50,51]. Event source locating experiment conducted at Fangshan coalmine in Beijing indicated that the accuracy was ± 500 m for the SAK-SYLOK system. When combined with two triaxial digital monitoring systems, the accuracy was improved to ± 200 m [52].

Three VGK seismography equipments were installed in December of 1968, at Fushun Municipal Seismology Bureau, completing the first seismic monitoring network in China that was capable of monitoring of mining-induced seismicity. The network had since been used for continuous monitoring of mining-induced seismicity at Fushun coalfield. The network was further expanded and improved to include four sub-networks in 1987, by adding seismic monitoring systems of 573, DD-1, and 768. Digital seismography equipments, JC-V100 and -V104, were added in 2000 and 2002, respectively, completing a seismic network with six sub-networks. A comprehensive research on mine microseismic event monitoring and prediction was carried at Fushun coalfield from 2002 to 2004 [11,14]. As part of the research program, additional four digital remote monitoring systems, which were capable of capturing seismic event with magnitude greater than $M_L = -0.3$, were installed. Source locating accuracy for events with $M_L \geqslant 1.0$ is ± 130 m for epicenter distance and ± 20 m for depth. To achieve this accuracy, all six surface seismic sub-networks were used. Polarization and wavelet identification techniques were applied to pick up first arrivals of P- and S-waves. The equal pseudo wave velocity (8.6 km/s) model was used in combination with the intersection method to determine the source locations. As a result of the early deployment of mine seismic monitoring systems, 37 years' continuous monitoring data are available at Fushun coalfield. Until July 31, 2005, 92,630 seismic events with $M_L \geqslant 0$ have been recorded at the mine site, positioning this mine as the record holder that possess the longest mine seismic monitoring record in China. Under the support of a research program (2004–2005) funded by Fushun municipal government, a high accuracy digital monitoring system (frequency range 0–120 Hz and sampling rates 50–1000 Hz adjustable) has been installed at Laohutai coalmine, which consists of six sensitive accelerometers and six velocity sensors [14,27]. The system is currently under calibration and will be put into operation soon.

Mine seismic monitoring systems, with a claimed source location accuracy of ± 100 m, were installed at Huafeng coalmine in Shandong Province and Sanhejian coalmine in Jiangsu Province. Due to the lack of high-quality system operators at the mine sites, the claimed monitoring accuracy was hardly achieved. Using the new monitoring system, 782 seismic events with $M_L \geqslant -0.3$ had been observed from January 2003 to March 2004. The seismic events are located at 500–1000 m depth and the highest magnitude ($M_L = 3.4$) was recorded on May 8, 2003 (Lu and Li, 2005, personal communication).

In summary, designated mine seismic event monitoring systems are only available at a few mines. The event detection and source locating accuracy of the systems still need further improvement. At mines without seismic monitoring systems, mine seismic recording relies heavily on rock noise reporting by miners.

5. Rockburst research

Rockburst research in China is governed in three major directions. Firstly, research is conducted to understand rockburst mechanisms, mitigate rockburst hazard, and increase mine safety. Secondly, research is carried out to ensure the public safety through alleviation of rockburst hazard to society. Thirdly, mine seismicities in underground mines have been viewed as resourceful information for natural earthquake study and one of the keys for earthquake prediction. Many researchers have devoted their time, effort, and resources into these areas of investigation and some of the works are reviewed in this section.

5.1. Rockburst mechanism

Studies in this area include rockburst classification, rockburst mechanism, rockburst-induced failure in underground mines and surface structures, short-term, long-term rockburst risk prediction and assessment, rock support in rockburst prevalent grounds, etc. Many internationally acknowledged theories and models are also well accepted in China. The Chinese researchers have conducted independent study in this area and proposed some theories and models, which will be reviewed briefly in this section.

Rockburst classification is one of the research topics that have drawn attentions from many investigators. Zhang et al. [53] classified rockbursts in coalmines into six categories through the combination of failure modes of coal body, stopes, and faults. In their classification, main energy sources and locations of energy release in each category are given. They also provide rockburst intensity classes and typical ranges of eight characteristic parameters such as damage radius, length of damaged drift, rockburst magnitude, measured energy, etc., in each class. Xu and Wang [54] classify rockburst intensities based on the ratio of σ_{max}/σ_c, where σ_{max} is the maximum tangential stress near an underground excavation and σ_c is the surface uniaxial compressive strength of the rock mass near the excavation. $\sigma_{\max}/\sigma_c = 0.3$ to 0.5, 0.5 to 0.7, 0.7 to 0.9, and 0.9 to 1.0 are classified as minor, moderate, severe, and extremely severe rockbursts, respectively. Pan et al. [1] classified coalmine rockbursts into three basic types due to compressive failure of coal seams, roof fracturing, and fault movement. Based on seismic wave analysis on data obtained from mines in Hunan Province, Tong et al. [55] concluded that the causes of mining-induced seismicity in Hunan were fault movement, ground fall, and rockbursting. Based on their extensive study of seismicity at Fushun coalmine, Cai [56] summarized the rockburst mechanisms at the mine as fault movement, roof fracturing, and pillar bursting. Recently, Li et al. [57] proposed a hierarchy classification of mining-induced seismicity. Five classes and 16 types of mining-induced seismic events are classified based on the influence of in situ tectonic stress field, physical and mechanical properties of rocks, rock mass structures, correlation between seismicity and mining activity, source of mining induced stress change, and the locations of seismic sources and rock mass failure. The advantage of this classification method is that it can identify the relationship between different types of rockbursts and assist in understanding the mechanism of mining-induced seismicity.

Another area of rockburst mechanism research is the development of models to explain the occurrence of rockbursts, from stress change to rock failure that leads to rockburst. The key seam model, proposed by Qian [2], states that the deformation of the key coal seam will lead to rock deformation above the mining area. The rock mass surrounding the stopes deforms and the structures that support the most rock load are considered as the building beams. According to the model, the rock beam thickness needs to satisfy the following relationship for structural stability:

$$h + h_1 \leqslant \frac{2\sigma_t}{\gamma}\left(\tan\phi + \frac{3}{4}\sin\theta\right)^2, \tag{2}$$

where h is the thickness of the key rock layer, h_1 is the thickness of the overburden layer which fractures along with the key layer, γ, σ_t, ϕ, and θ are the density, tensile strength, internal friction angle, and rotation angle of the fractured key layer, respectively. The model explains many observed rock mass behaviors and responses such as floor failure and water outburst, rock layer movement and layer separation, loading of the building beams and the stability of the key seam, the S–R stability (slip and rotation stability) of the building beams, rock stress change, and rockbursts [2].

A rock beam model, proposed by Song [58], considers that the interlocking of the fractured rocks can transmit loads to the rock ahead of the face and to the muck in the mined stopes. Consequently, the beam load is not fully supported by the rock support system. Rock load acting on the rock support system depends on the resistance to the movement of the rock beam [58].

The model based on energy accumulation and release due to stress change, proposed by Cai [56], views the rockburst as the process of energy accumulation and release in rocks as the mining activities disturb the in situ stress field. The model intends to explain the influence of mining rate, depth, location, and field stress on the triggering of rockbursts. The concept of mining disturbance potential is proposed. The mining disturbance potential (G) is proportional to the mining depth (H) and excavation volume (ΔV) and decreases as the shortest distance (L) between the mining stope and the nearest geological structure increases. Therefore, energy accumulation inside the rock due to mining excavation can be expressed as

$$\sum E = AG^D k_0 = A\left(\frac{H\Delta V}{L}\right)^D k_0, \tag{3}$$

where A is a parameter reflecting the influence of mining method on rockburst, k_0 is a coefficient, and D is a constant. The model has been applied to study rockburst problems at Laofutai mine and the results are satisfactory [59].

Based on the relationship between fractal number and fractal radius, Xie [60] studied seismic event location distribution using fractal theory. He found that the accumulation of microseismic events in temporal and spatial spaces followed fractal structure. The degree of event accumulation increased substantially before a big rockburst [60]. The fractal dimension decreases as the micro-factures in the rock increases and the minimum fractal dimension can be found close to the occurrence the major fracture or rockburst. It is suggested that based on the decrease of the fractal dimension of microseismic events, it is possible to predict the major rockbursts in mines [61].

Tang and Wang [62] proposed a new rockburst proneness index by considering the elastic energy storage capacity in the rock, the relationship between energy accumulation and dissipation, and the simplicity and reliability in determining the index. The index is defined as

$$k = \frac{\sigma_c}{\sigma_t}\frac{\varepsilon_f}{\varepsilon_b}, \tag{4}$$

where σ_c and σ_t are the uniaxial compressive strength and the tensile strength of the rock, and ε_f and ε_b are the total strain before and after the peak strength in an uniaxial compressive test. This index overcomes the shortcomings of using either only σ_c/σ_t or $\varepsilon_f/\varepsilon_b$ as rockburst proneness index [62].

5.2. Rockburst risk assessment, control, and prediction

Over the last few decades, extensive researches have been conducted in China for rockburst risk assessment, rockburst damage control, warning system development, and rockburst prediction and prevention.

For rockburst risk assessment, the methods applied include back-analysis, regression analysis, numerical analysis, correlation to regional stress field, seismology method, fractal theory, extreme value theory, statistics, rockburst tendency method, etc. To control rockburst hazards, methods commonly used in China include water injection, de-stress blasting, de-stressing by drilling of large diameter holes, rock fracturing using mechanical vibration, mining of specific layer to release stress, treatment of stiff roofs, wider drift development, rock support, placement of coal pillars, mining process optimization and management, etc. [1]. To predict rockburst, various methods, such as drill bit, stress measurement, deformation measurement, acoustic emission, microseismic monitoring, electromagnetic radiation, seismology, etc., have been tried and experimented. For example, drill bit and electromagnetic radiation methods have been applied to rockburst monitoring at Sanhejian coalmine in Jiangsu Province and the results were satisfactory [53,63,64]. Blast de-stressing technique was also used at the mine, in areas where electromagnetic radiation was abnormal, to release excessive stresses for rockburst control.

Extensive rockburst research had been conducted at Mentougou coalmine in Beijing [44,51]. About 547 rockburst events were recorded at the mine site from 1949 to 1997, and about 300 events happened before 1980s. From 1949 to 1980, more than a dozen people were killed and the drifts and mining equipments were severely damaged due to rockburst at the mine. Although many destructive rockbursts had happened at the mine since 1980s, casualties were greatly reduced due to the installation of advanced seismic monitoring systems and the research on rockburst risk assessment and prediction [65].

Researchers from the Beijing University of Science & Technology and Fushun Municipal Seismology Bureau have conducted extensive studies on the mine seismicity at Laohutai coalmine [56,66–68]. The researches included detailed in situ stress measurement, extensive geological investigation, rock mechanics testing, and field monitoring at the mine. Based on the model of energy accumulation and release, they found a pattern of rockburst occurrence time, spatial distribution, and intensity. A mining disturbance potential model was developed for the prediction of rockbursts. The correlation between rockburst and mining quantity, mining depth, fault, and field stress was established. Many other research works were conducted at other coalmines at Fushun coalfield. The research results had greatly benefited local mining companies in rockburst prediction and prevention.

Abnormal ground deformation, groundwater outflow, and ground noise were observed during the massive roof fall at Jinhuagong coalmine in Daitong city on May 25, 1975. These abnormal phenomena are usually associated with natural earthquakes and are considered as informative seismological features for earthquake prediction. The same abnormal phenomena were observed on May 31, 1975 and an alert was issued. Massive roof fall happened on the same day but no one was hurt. More than three hundred seismic events with $M_L \geqslant 0.5$ were recorded and the maximum event was $M_L = 2.1$. In total, 1.622×10^6 J of energy was released, equivalent to an earthquake at $M_L = 2.9$ [40]. It was summarized from field monitoring data that microseismic event activity increased gradually both in event frequency and magnitude before major roof falls. Recorded seismic waves show that all P-wave first arrivals were downwards, and the wave attenuation was quick. Groundwater dripping in the roof increased substantially a few days before major roof falls. Change of water color from clear to dirty was also a sign of pending roof fall.

One field monitoring of fault displacements was conducted at Taiji coalmine [24]. The hypothesis was that strong rockburst events were influenced by major structures such as faults at the mine site. Fault deformation measurement was conducted at −550 and −700 m levels. It was found the fault deformation was small at the −700 m level but large at the −550 m level (where large mining stopes were excavated). Fault deformations at the upper level correlated weakly to the mining activities at the lower level (where the mining activity was limited) but the overall deformation trend was that the deformation vectors were pointing towards the mining stopes. Fault deformation rate tended to increase before strong rockburst events. Seventy differential leveling measurements were conducted in a monitoring line across the F_{12} fault. Relative fault movements were observed during seven large rockbursts ($M_L = 1.6$–3.2). The relative fault movements were in the range of 1.4–5.5 and 0.1–61.9 mm before and after the main shocks, respectively. In general, the upper plate moved downwards before the main shocks and upwards thereafter. It was concluded that the balanced stress state in a large volume of the mining area could be disturbed by the mining activity. Once the critical balanced stress state is perturbed, fault movement may occur, leading to large rockbursts.

5.3. Natural earthquake study based on mining-induced seismicity investigation

Chinese seismologists were renowned for the successful prediction of the occurrence of a large natural earthquake ($M_L = 7.3$), which occurred on February 4, 1975 in Haicheng city, Liaoning Province. The seismologists sent out warnings days before the earthquake. People in nearby cities remained outdoors, despite the cold weather. As a result, many lives were saved.

As stated before, some researchers are conducting earthquake prediction experimental study at mine sites with active mine seismicity because of the similarities between mining-induced seismic events and naturally occurring earthquakes. A seismically active mine is considered as an ideal km-scale in situ laboratory for conducting research on earthquake prediction.

Mentougou and Fangshan coalmines in Beijing are such in situ km-scale geophysics laboratories studied by some seismologists [52,69–71]. The idea was first proposed in 1992 [52]. A SAK-SYLOK seismic monitoring system and two digital triaxial sensor systems were installed at Fangshan coalmine. Microseismic activities before rockbursts were closely monitored using equipments with two different frequency bands, 10–300 and 5–100 Hz. Attempts were made to predict rockbursts based on the integration of collected ground noise, microseismicity, and mine geophysics information. The study on the source mechanism of seismic events right before the destructive rockburst [70] indicated that 20 days before the $M_L = 2.3$ rockburst event, there was an increase of sub-critical events. The event increase was periodic. At the time of rockburst, the rock volume in the area of potential rockburst increased rapidly. Right before the rockburst, the sub-critical event increase was accompanied with the generation of long-period events and small events.

Abnormal groundwater variation in coalmines was studied by some seismologists for rockburst prediction [72]. At Taozhuang coalmine in Shandong Province, observation of the groundwater levels in the mine showed that weak evidence of abnormal groundwater behavior could be observed before strong mine seismic events. The study of correlation between rockbursts and dynamic monitoring of mine-wide groundwater confirmed that reliable abnormal information can be captured before rockburst events [15,73]. Che et al. [73] produced the theoretical groundwater variation curves based on the relationship between the measured groundwater levels and the Earth's gravity tide levels the day before the rockburst. The predicted groundwater curves were compared to the measured ones to identify the abnormality. It was found from 43 case studies that 38 cases (or 88.4%) showed abnormal groundwater level variations right before the rockburst events. The percentages of abnormal groundwater decrease, increase, and fluctuation are 58%, 21%, and 21%, respectively. A few examples showing the abnormal groundwater variations are presented in Fig. 17. The magnitudes of abnormal groundwater level variations are linearly proportional to the magnitudes of the rockbursts and decrease as the distances between the wells and the rockburst hypocenters increase. According to Che et al. [73], measured groundwater curves agreed to the predicted ones when there were no rockburst events.

Another km-scale in-situ laboratory study was conducted at Laohutai coalmine in Liaoning Province [74–78]. Extensive investigation of the mine seismicity were carried out which included the study of sequential characteristics, mechanism of mining-induced seismicity, change of geophysical properties before strong events, trend analysis of extreme values of seismic intensity, and correlation between gas outbursts and rockbursts. It was found that

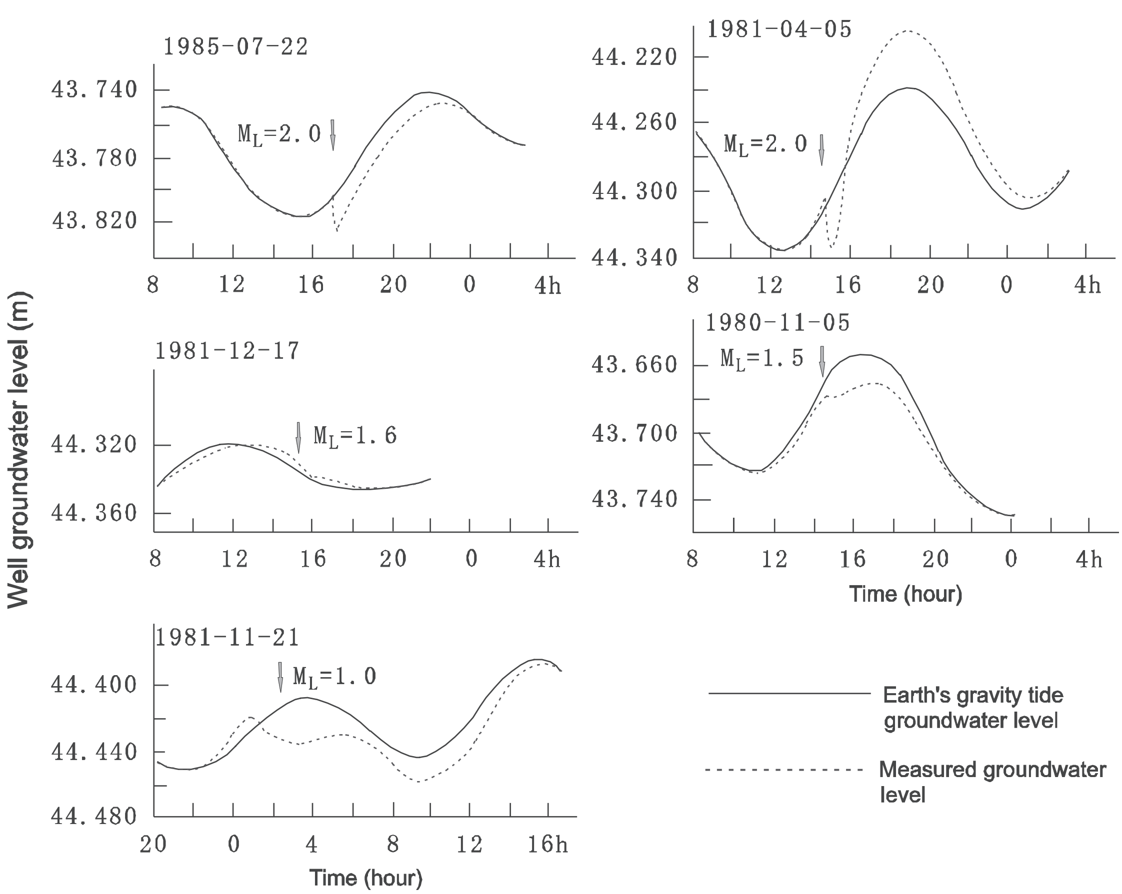

Fig. 17. Abnormal groundwater level variations before rockbursts [73].

seismic events with $M_L \leqslant 1.5$ were closely related to mining activities, and the occurrence of the event associated well with the timing of the mining activities. The correlation of seismic events, with $M_L > 1.5$, to mining activity was not strong. Furthermore, for events with $M_L \geqslant 2.9$, a strong correlation to tide gravitational force was noticed. It was suggested that information about the velocity ratio, tide deformation, abnormal gas disembogue, change of loading and unloading response ratio and other abnormality of earthquake activities could be used for the prediction of the occurrence of earthquakes. The loading (unloading) response is defined as the inverse of the Young's modulus during loading (unloading). The ratio is close to 1 at the elastic stage and increases drastically near peak strength. In coalmines, the correlation of gas outbursts and rockbursts is very strong, especially at depth. A different type of rockburst, or gas outburst-rockburst, can be triggered by the coupling effect of unloading of confining stress due to mining and desorption and expansion of high-pressure gases. In addition, high-pressure gases can contribute to the formation of rockbursts. As a result, the rockburst and abnormal gas gush can be used as warning signals interchangeably [74–79].

Some books and software have been produced in the field of rock mechanics and rock engineering and many of them cover the topic of rockburst study. Although this review is not intended to provide a complete list of these works, some representative ones have been provided in the reference list [2,17,58,80–86].

6. Future trends

6.1. Future trends of mining-induced seismicity hazards

The minerals resource development usually starts at shallow ground and gradually proceeds to deep ground. Most mining-induced seismic activities happen at coalmines in China. The average mining depth in 1980 was about 288 m in coalmines. In 2000, it had increased to 500 m, an increase of 212 m in 20 years. Therefore, recent increase of mine seismicity is largely attributed to the increase of mining depth. By 2003, 83% and 76% of coals had been mined out above the depth of 600 and 1000 m, respectively (Fig. 18). In addition, the mine stopes are becoming larger as mining activities progress deeper [11]. According to statistical data from the Department of Production Coordination, Ministry of Coal in China, the number of shallow coalmines (depth < 400 m) will decrease considerably. Medium depth mines (400–800 m) will increase substantially and the number of deep mines (800–1200 m) will increase drastically. Super deep coalmines (depth > 1200 m) are also on the development agenda in the future (Fig. 19) [87].

Coal energy, the base for economic development and society, constitutes 70% of the primary energy consumption in China. The Chinese economy is growing at an unprecedented high speed, which in turn put great pressure

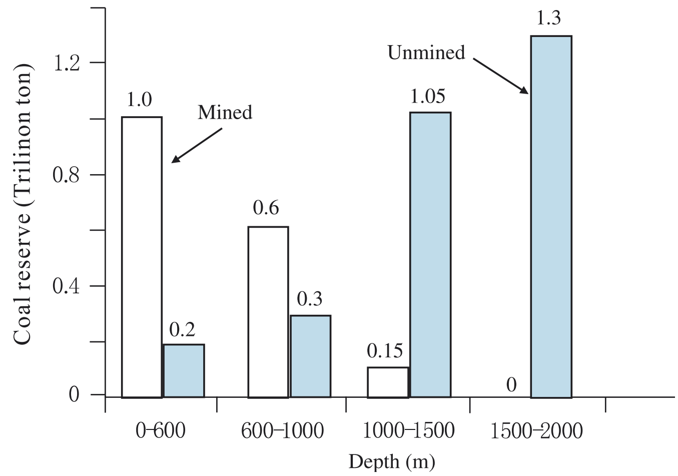

Fig. 18. Coal reserve depth distribution in China (1995 statistics).

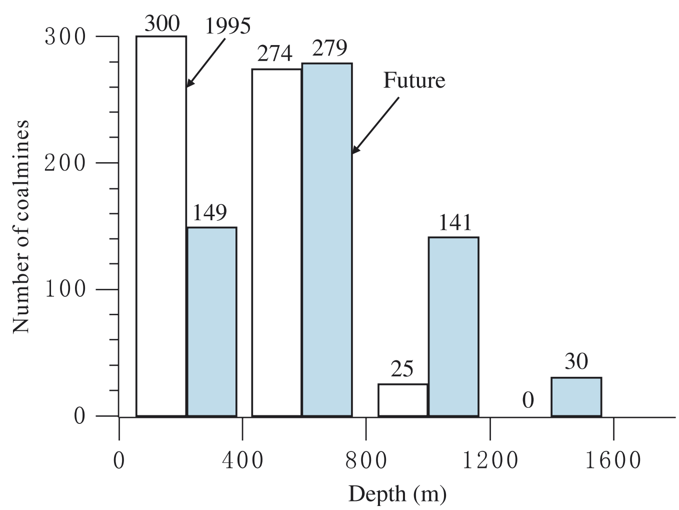

Fig. 19. Mining depth distribution of 599 state-owned key coalmines in China.

Table 5
Output of coals from 2000 to 2004 in China

Year	2000	2001	2002	2003	2004
Output (billion ton)	0.99	1.1	1.39	1.736	1.956

on energy supply. The demand for coal is very high and the coal production has been increased consecutively over the last few years (see Table 5). The demands for coal in 2010 and 2020 are estimated at 2.2 and 2.5 billion tons, respectively [88]. Shallow coal resources will dry up eventually and deep mining is inevitable. It has been known that as mining depth and volume of extraction increase, not only the occurrence of mining-induced seismic events but also the frequency and scale of the seismic events will increase. It is envisioned that the mine seismicity hazard will become very challenging in the future,

Table 6
List of seismology network for reservoir-induced earthquake monitoring in China

Reservoir name	Location	Basin	No. of sub-network	Monitoring lower bound (M_L)	Network completion time
Three Gorges	Hubei	Yangtze River	26	0.5	2000.7
Xinfengjiang	Guangdong	Xinfeng river	8	0.5	1980.10
Danjiangkou	Hubei	Hanshui River	4	1.0	
Ertang	Sichuan	Yalong River	9	0.5	1992.5
Geheyan	Hubei	Qinjiang River	7	0.5	1995.4
Daqiao	Sichuan	Anning River	6	0.8	1996.7
Xiaolangdi	Henan	Yellow River	9	0.5	1996.7
Manwan	Yunnan	Lanchan River	3	1.5	2002.5
Longyangxia	Qinghai	Yellow River	7	1.0	1986
Shuikou	Fujian	Minjiang River	5	1.0	1996
Three Gorges (phase I)	Hubei	Yangtze River	6	0.5	1996.12
Tianshenqiao 1	Guangxi–Guizhou	Red River	6	1.0	1997.5
Lijiaxia	Qinghai	Yellow River	5	1.0	1998.4
Kezier	Xinjiang	Weigan River	5	1.0	1999.12

transforming the mine safety problem into a public safety problem.

6.2. Government policy and regulations

The Chinese government has passed several laws regulating the safety of mines, especially the prevention and mitigation of mining-induced seismic hazards. Clause 18 of the Bill, Law of the People's Republic of China on Safety in Mines, passed on November 7, 1992 by the Congress, states that mining companies must take preventive measures to deal with potential mine safety hazards such as rockbursts. Clause 19 of the Guideline on the Implementation of the Law of the People's Republic of China on Safety in Mines, issued by the Ministry of Labor on October 30, 1996, states that mine production in rockburst prone grounds must provide special design documents for approval. The Law of the People's Republic of China on Safe Production, passed by the Congress on June 29, 2002, specifies that mine development must meet the safety requirement and have a safety assessment. With the relevant laws passed and law enforcement enhanced, it is seen that lawful management of mine safety and public safety in China can be achieved in the future.

6.3. Integration of regional seismology network for mine seismicity monitoring

Long-term observation of the studied objective is the key to most major scientific discoveries. The study of the mechanism of mining-induced seismic hazard, hazard prevention and mitigation measure development all require long-term monitoring of the seismic activities.

The Seismology Bureau of China has a nation-wide seismology network. This network had played an important role in the monitoring of reservoir-induced earthquakes and volcanic activities. Reservoir-induced earthquake monitoring started in China in the early 1960s when this type of tremor was first noticed after the completion of Xinfengjiang hydropower complex. Initially, the monitoring was conducted purely by human observation. Later, special analog remote monitoring system designated for reservoir-induced earthquake monitoring was built. Nowadays, the digital monitoring networks have been installed at some of the large-scale hydropower project sites such as Three Gorges Projects and Manwan Dam sites. A list of the reservoir seismic monitoring network is presented in Table 6 [89]. Like reservoir-induced earthquakes, mining-induced seismicity endangers not only mine personnel and rock structure safety, but also public safety. An effort has been made by the Seismology Bureau of China to integrate the nation-wide seismology network to assist the monitoring and research of rockbursts in underground mines.

Mining-induced seismic hazard is inevitable as human beings peruse underground mining activities. This type of hazard is a geophysical hazard. Hence, it is a logical choice to combine mining engineering with geophysics for the research and mitigation of the hazard. Many co-investigations involving researchers from both fields have been conducted in an effort to promote rockburst research. As the monitoring technology is improved and the accumulation of high quality observation data continues, it is believed that further developments in rockburst mechanism study, prediction, control, and mitigation can be achieved in the near future.

7. Conclusions

Rockburst hazards exist in almost all deep mines in China. Traditionally, rockbursts are considered unlikely in soft rock mines, but when mining activities progress deeper, rockburst hazards may also occur. One example is Quantai coalmine in Jiangsu Province. The uniaxial compressive strengths of the shale in the roof and on the floor are 20 and 10 MPa, respectively. Rockburst happened at the depth of 700–800 m [90–96]. Rockbursts have been reported at some shallow mines where the tectonic stress activity is high. The occurrence of rockburst and its level of activity depend on the mining depth and the current tectonic stress field. In general, shallow minerals resources will dry up and mining activity is inevitably progressing deeper. Consequently, rockburst hazard will increase and further studies are needed for the understanding of the rockburst mechanism, rockburst prediction, control, and mitigation. Relevant laws have been passed by the Congress to ensure that rockburst hazards be handled lawfully and responsibly.

It is found that a strong correlation between rockburst and gas outburst exists in deep coalmines. In most cases, high gas concentration indicates that the coal body has been fractured. Because high accurate microseismic event monitoring is an effective method to detect rock mass fracture initiation and propagation, it can be used for early warning of high gas concentration. This warning signal can be given prior to the warning provided by the direct observation by gas sensors. It is recommended to conduct microseismic event monitoring in coalmines to monitor not only the rockburst potential but also the gas outburst potential. We find that the rockburst and gas outburst can be used as warning signals interchangeably. To control and mitigate rockburst hazard in deep mines, we need to promote the high-resolution mine microseismic monitoring system to mines and train technicians to operate the system properly.

Rockburst is a hazard to mine personnel and underground infrastructures as well as surface structures. But at the same time, rockburst is a resource for natural earthquake study. The Chinese seismologists and geo-physicians have attempted to study natural earthquakes and geophysical problems in deep ground through the study of rockbursts in mines. Some breakthroughs in this study area are expected in the near future.

Acknowledgments

This study was funded in part by the National Natural Science Foundation of China (NSFC) under the Contract nos. 40244021 and 50490271, the Science and Technology Foundation of Liaoning Province under the Contract no. 2003231003, and by the Natural Science Foundation of Liaoning Province under the Contract no. 20042184.

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