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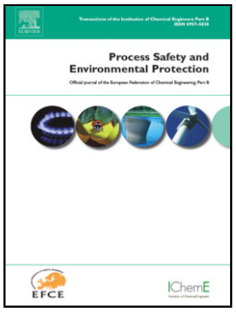

Title: Focusing on the patterns and characteristics of extraordinarily severe gas explosion accidents in Chinese coal mines

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Focusing on the patterns and characteristics of extraordinarily severe gas explosion accidents in Chinese coal mines

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Highlights

- This study mainly focuses on extraordinarily severe gas explosion accidents (ESGEAs) in Chinese coal mines.
- Disorganized ventilation fan management and illegal blasting were the most prominent causes of ESGEAs.

- ESGEAs are linked with the operating locations, occurrence time, regions and ownership of the coal mines.

ABSTRACT

Extraordinarily severe gas explosion accidents (ESGEAs) (thirty fatalities or more in one accident) have a high occurrence frequency in Chinese coal mines. There are 126 ESGEAs that occurred in China from 1950 to 2015, and they were investigated through statistical methods in this study to review the overall circumstances and to provide quantitative information on ESGEAs. Statistical characteristics about accident-related factors, such as gas accumulation, ignition sources, operating locations, accident time, coal mine regions and coal mine ownership, were assessed in this paper. The statistical analysis shows that disorganized ventilation fan management was the most frequent cause of gas accumulation in ESGEAs, while illegal blasting was the most prominent cause of the ignition source in ESGEAs. Furthermore, ESGEAs were found to occur frequently in certain provinces (e.g., Shanxi, Henan and Heilongjiang) and during November and December of the year. Moreover, most accidents and the largest death tolls generally occur in state-owned coal mines. Based on the results of statistical studies, some countermeasures were proposed in this study.

Key words: Coal mine; Gas explosion; Extraordinarily severe accidents; Accident statistics; Countermeasures

1. Introduction

During the past 15 years, the Chinese government and State Administration of Work Safety (SAWS) has enhanced safety supervision and investment for coal mines, which has greatly improved the safety in the coal mine industry. In 2001, the State Administration of Coal Mine Safety (SACMS) reported that there were 5670 deaths and a death rate per million tons (DRPMT) of 5.07. This fell to 588 deaths and a DRPMT of 0.159 in 2015 (Fig. 1) (Chen et al., 2012; SACMS, 2017). Although the deaths and DRPMT have steadily decreased, ESGEAs still occur. Recent examples include the following: at 11:33 am on 31 October 2016, an ESGEA occurred in the Jinshanggou coal mine, Yongchuan district, Chongqing City, which killed 33 miners, and at 11:30 am on 3 December 2016, an ESGEA occurred in the Baoma mining company, Chifeng city, Inner Mongolia, which killed 32 miners (SACMS, 2017). By comparison, no ESGEAs occurred in coal mines in America and Australia from 2001 to 2015, though there were some gas explosions in the USA (Sago 2006 and Upper Big Branch 2010) (Gao et al., 2016; Wu et al., 2011).

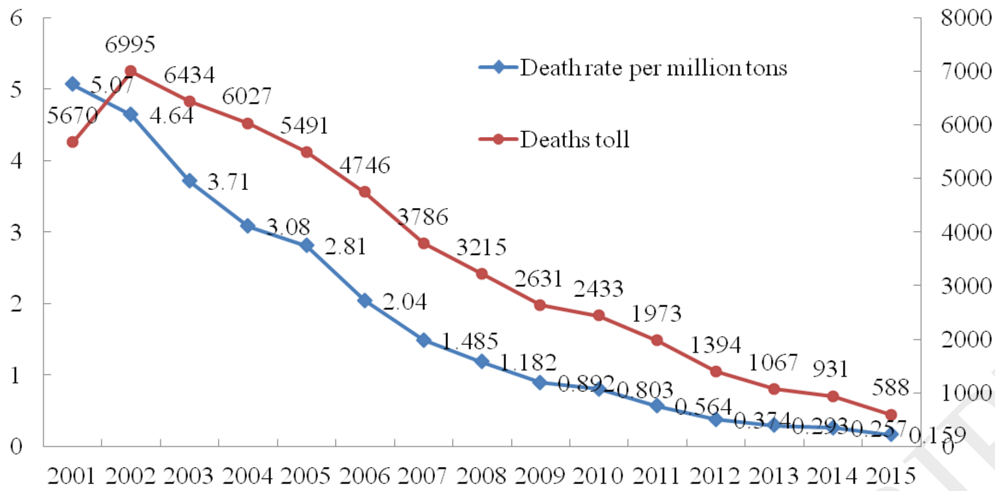

Fig. 1. Death toll and rate in Chinese coal mines from 2001 to 2015

In the past 15 years, a number of significant preventive measures have been introduced by the Chinese government and SACMS in order to reduce gas explosion accidents, which include the following:

- Enhancement of coal mine safety legislation;
- Establishment of an independent coal mine safety supervision system;
- Implementation of 200 gas control demonstration mine projects;
- Investment in new equipment and technology for gas removal and gas monitoring; and
- Promotion of a new mine safety refuge system with "six subsystems": monitoring and control system, staff location system, rescue water supply system, self-help system of pressure ventilation, communication system, and emergency rescue system.

The combined efforts of the Chinese government, SACMS and coal mine companies through the implementation of safe management and technological equipment to prevent gas explosions have resulted in great progress and development from 2001 to 2015. Despite these efforts, 926 fatal gas explosion accidents (killing three people or more in one accident) occurred and 8833 people died (SACMS, 2017). Among them, 42 accidents were ESGEAs with 2598 deaths, which accounted for 5% of the total fatal accidents and 29% of the death toll (SACMS, 2017). This highlights that the control or elimination of ESGEAs is crucial to significantly reduce the death toll in Chinese coal mines.

Currently, researchers have focused heavily on coal mine gas explosion accidents and have published numerous papers (Amyotte et al., 2009; Chen et al., 2012, 2013; Gao et al., 2016; Lenné et al., 2012; Li et al., 2010, 2013; Oh et al., 2001; Patterson et al., 2010; Wang et al., 2014; Xiao et al., 2010; Yin et al., 2013; Zheng et al., 2009), but there is a lack of study on ESGEAs. In fact, the ESGEAs that occurred most frequently in Chinese coal mines had similar characteristics and causes, which suggests that lessons can be learned from past ESGEAs. Hence, the purpose of this paper is to study the patterns and characteristics of ESGEAs in Chinese coal mines from the viewpoint of the gas accumulation, ignition sources, operating locations, accident time, coal mine regions and coal mine ownership. The results of this study are helpful for the prevention of ESGEAs and the improvement of safety in Chinese coal mines.

2. Background analysis

According to the “Coal Mine Production Safety Accidents Report and Investigation Handling Regulation” issued by the State Administration of Work

Safety (SACMS, 2017), accidents are classified into four categories based on death, injury and property loss (Table 1): (1) Ordinary; (2) Major; (3) Severe; and (4) Extraordinarily Severe. This classification applies for gas explosion accidents, e.g., an accident with 1-2 fatalities is an ordinary gas explosion accident, 3-9 fatalities is a major gas explosion accident, 10-29 fatalities is severe, and 30 or more fatalities is extraordinarily severe. According to this classification, Table 2 summarizes the frequency and deaths of major, severe and extraordinarily severe gas explosion accidents in Chinese coal mines from 2001 to 2015 (SACMS, 2017). This shows that ESGEAs have a much lower occurrence frequency and higher death rate compare to major and severe accidents. Moreover, ESGEAs have caused substantial losses to both the international image of China and coal enterprises, especially in miners' lives and health. It is thus important that Chinese coal enterprises eliminate ESGEAs.

Table 1 The classification of coal mine accidents in China

Accident grade	**Ordinary**	**Major**	**Severe**	**Extraordinarily Severe**
Deaths	<3	$\geq 3, <10$	$\geq 10, <30$	≥ 30
Serious injuries	<10	$\geq 10, <50$	$\geq 50, <100$	≥ 100
Property loss	$<¥10^7$	$\geq ¥10^7, <¥5\times10^7$	$\geq ¥5\times10^7, <¥10^8$	$\geq ¥10^8$

Table 2 Frequency and deaths of major, severe, and extraordinarily severe gas explosion accidents in Chinese coal mines from 2001 to 2015

Year	**Accident Grade**					
	Major		**Severe**		**Extraordinarily Severe**	
	Frequency	**Deaths**	**Frequency**	**Deaths**	**Frequency**	**Deaths**
2001	86	461	24	363	6	280
2002	112	454	24	396	6	318
2003	72	429	18	318	6	325
2004	103	398	15	242	6	453
2005	75	314	27	452	7	597

2006	75	445	12	212	4	143
2007	51	266	12	186	2	136
2008	36	190	4	84	/	/
2009	37	150	4	51	3	262
2010	25	136	6	82	/	/
2011	22	114	8	118	/	/
2012	9	52	3	46	1	48
2013	6	36	7	135	1	36
2014	2	9	3	47	/	/
2015	4	20	2	29	/	/
Total	715	3474	169	2761	42	2598

Note: Data are from the Online Accident Inquiry System of SACMS

Table 3 shows the 184 cases of extraordinarily severe coal mine accidents (ESCMAs) in China from 1950 to 2015 (SAWS, 2005; SAWS, 2007; SACMS, 2017; Wang and Li, 2002). The ESCMA categories in Chinese coal mines are gas explosion, coal and gas outburst, coal dust explosion, and fire and mine inundation. For these accidents, ESGEAs occurred 126 times and caused 7502 fatalities (Table 3) (SAWS, 2005; SAWS, 2007; SACMS, 2017; Wang and Li, 2002), which accounts for 69% and 66% of the total, respectively. In total, gas explosion accidents have the highest frequencies and fatalities. Even worse, there were 17 cases of the most extraordinarily severe gas explosion accidents (more than 100 fatalities in one accident) that occurred and caused 2346 fatalities (Table 4) (SAWS, 2005; SAWS, 2007; SACMS, 2017; Wang and Li, 2002). Thus, in both accident frequency and death toll, ESGEAs are the major contributor and should be given more attention to prevent coal mine accidents.

Table 3 Frequency and deaths for different types of extraordinarily severe coal mine accidents during 1950-2015

Accident types	Frequency	Percentage (%)	Deaths	Percentage (%)
Gas explosion	126	69	7502	66

Coal and gas outburst	10	5	509	5
Coal dust explosion	13	7	1462	13
Fire	12	6	617	5
Mine inundation	20	11	1098	10
Other	3	2	117	1
Sum	184	100	11305	100

Note: Data are from the China Coal Mine Accidents and Experts Review, Extraordinarily Severe Accidents with Collection Cases and Online Accident Inquiry System of SACMS.

Table 4 ESGEAs with more than 100 deaths in Chinese coal mines from 1950 to 2015

Date	**Province**	**Mine name**	**Ownership type**	**Accident type**	**Deaths**
1950-02-27	Henan	Yiluo Coal Mine	State-owned	Gas explosion	187
1954-12-06	Neimenggu	Dafa Coal Mine	State-owned	Gas and coal dust explosion	104
1960-11-28	Henan	Longshanmiao Coal Mine	State-owned	Gas explosion	187
1960-12-15	Chongqing	Zhongliangshan Coal Mine	State-owned	Gas and coal dust explosion	124
1975-05-11	Shaanxi	Jiaoping Coal Mine	State-owned	Gas and coal dust explosion	101
1977-02-24	Jiangxi	Pinghu Coal Mine	State-owned	Gas explosion	114
1981-12-24	Henan	Fifth Mine of Pingdingshan Mining Bureau	State-owned	Gas and coal dust explosion	133
1991-04-21	Shanxi	Sanjiaohe Coal Mine	State-owned	Gas and coal dust explosion	147
1996-11-27	Shanxi	Dongcun Coal Mine	Township-owned	Gas and coal dust explosion	114
2000-09-27	Guizhou	Muchonggou Coal Mine	State-owned	Gas and coal dust explosion	162
2002-06-20	Heilongjiang	Chengzihe Coal Mine	State-owned	Gas explosion	124
2004-10-20	Henan	Daping Mine	State-owned	Gas explosion	148
2004-11-28	Shaanxi	Chenjiashan Coal Mine	State-owned	Gas explosion	166
2005-02-14	Liaoning	Sunjiawan Coal Mine	State-owned	Gas explosion	214
2005-12-07	Hebei	Liuguantun Coal Mine	Private-owned	Gas and coal dust explosion	108
2007-12-05	Shanxi	Ruizhiyuan Coal Pty Ltd	Private-owned	Gas explosion	105
2009-11-21	Heilongjiang	Xinxing Coal Mine	State-owned	Gas explosion	108

Note: Data are from the China's Coal Mine Accidents and Comments of Safety Specialists, Extraordinarily Severe Accidents with Collection Cases and Online Accident Inquiry System of SACMS

3. Data and Methods

3.1 Data Sources

In this paper, 126 ESGEAs (Appendix A) were collected from China's Coal Mine Accidents and Comments of Safety Specialists (1949-2000) (Wang et al, 2002), which contains the mine profiles, accident processes, accident causes and accident consequences and is the most authoritative source for coal mine accident statistics in China; the Extraordinarily Severe Accidents with Collection Cases (2000-2003) and (2004-2005) (SAWS, 2005; 2007), which include the accident investigation reports and handling accident reports; and the Online Accident Inquiry System of State Administration of Work Safety of China (SACMS, 2017), which collects information on the accident time, coal enterprise, coal mine region, death toll and accident causes.

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3.2 Methods

Patterns and characteristics of industrial accidents can be analyzed through the frequency of accident occurrences in a given period, such as chemical accidents (Duan et al., 2011; Kourniotis et al., 2000; Zhang et al., 2012), petrochemical accidents (Konstandinidou et al., 2006; Tahhan et al., 2009; Nivolianitou et al., 2006), and fire accidents (Chettouh et al., 2002; Chettouh et al., 2016; Yang et al., 2012). Recently, more researchers have also used this method in their papers, such as Chen et al. (2012), Wang et al. (2014), Gao et al. (2016) and Yin et al. (2017). In this study, this method is used to investigate the statistical patterns and characteristics of ESGEAs in Chinese coal mines from 1950 to 2015.

4. Statistical analysis on the characteristics of ESGEAs

4.1 Gas accumulation and ignition source

For a gas explosion to take place, there are three necessary conditions: (1) the methane gas concentration reaches between 5% and 16%; (2) the oxygen concentration is more than 12%; and (3) there is an ignition source temperature of at least 650-750°C with sufficient energy. The oxygen concentration is normally more than 12% in underground coal mines due to mechanized ventilation, so in this study, only the gas accumulation and ignition sources of ESGEAs are analyzed.

Table 5 shows the frequency distribution of gas accumulations that occurred under different conditions. Disorganized ventilation fan management was the most frequent cause for the gas accumulation of ESGEAs, which accounted for 35% of the total. Furthermore, irrational ventilation system design and chaotic ventilation facilities management were the main causes of gas accumulation that accounted for 21% and 19% of the total, respectively. In addition, it is noteworthy that local fans stopping due to power failure, local fans with recirculating air and series ventilation are the three risk types that frequently occur in the data, which means that these events frequently occur in incidents of gas accumulation. Therefore, the safety engineer should take measures to better manage the ventilation equipment and facilities and optimize the ventilation system as the main methods of preventing gas accumulation in underground coal mines. For example, the ventilation fan and ventilation duct should have designated personnel for management, and the inspection and maintenance system should be constructed perfectly to provide an adequately effective air volume; the local ventilation fan should be installed with a special transformer, special switch and special circuit in order to ensure a steady, reliable flow of electricity; the alternative main fan or local fan system should be strictly implemented in Chinese coal mines to avoid malfunctions in the ventilation fan that result in long durations with no air supply.

Table 5 Frequency distribution for the gas accumulation of ESGEAs in Chinese coal mines

Type	Direct cause	Frequency	Percentage (%)
Disorganized ventilation fan management	Local fan stalling due to power failure	17	35
	Turning the local fan on and off casually	7	
	Local fan that is uninstalled or being installed	3	
	Uninstalled main fan	4	
	Local fan with recirculating air	13	
Chaotic ventilation facilities management	Ventilation duct crevasse with serious air leakage	5	19
	Ventilation duct with serious pressure	3	
	Ventilation duct without extension to the heading face	9	
	Ventilation duct disjunction	4	
	Sealed wall broken and unrepaired	3	
Irrational ventilation system design	Ventilation system with no or poor design	7	21
	Series ventilation	11	
	Short circuit of ventilation	8	
Local gas accumulation	Gas accumulation in gob area	10	12
	Gas accumulation in blind roadway	3	
	Gas accumulation in upper corner	2	
Sudden change in geological conditions	Roof falling with abnormal gas-effusion	7	9
	Coal and gas outburst	5	
Poor roadway management	Roadway ventilation with air leakage	3	4
	Serious blockage of the roadway section	2	

Table 6 summarizes 30 primary types of ignition sources and their frequencies. Illegal blasting was the most prominent ignition source of ESGEAs that resulted in 44 accidents and accounted for 35% of the total ESGEAs. In addition, electromechanical equipment that is not explosive resistant and the illegal operation of cap lamps were two important causes of ignition sources that accounted for 25% and 9% of the total ESGEAs, respectively. Overall, illegal blasting and electromechanical equipment that is not explosive resistant were the two leading causes of ignition source of ESGEAs leading to 76 accidents, which accounted for 60% of the total. Further analysis of the direct causes reveal that blasting with an inadequate sealed hole, cable breakage or bare cable joints and coal electric drills that are not explosion resistant are the top three ignition sources, which indicates that the safety engineer should pay more attention to the blasting procedure and key equipment management. Based on the above analysis, standardizing the blasting procedure and creating a management system for the electromechanical equipment are critical to reduce the potential ignition sources of ESGEAs. For instance, blasters and electricians should have more safety training than ordinary miners in order to enhance their occupational skills and safety awareness, and an effective penalty system should be established for unsafe behavior; electromechanical equipment should have a strict system of purchase, check and acceptance, usage and maintenance, and assigned special personnel to patrol key equipment (e.g., the cable, coal electric drill and local fan) during daily work to ensure a stable and reliable quality.

Table 6 Frequency distribution of ignition sources of ESGEAs in Chinese coal mines

Type	Direct cause	Frequency	Percentage (%)
Illegal blasting	Blasting with inadequate sealed hole	13	35
	Blasting without the use of water stem	9	
	Blasting with inadequate resistance line	4	
	Bulldozing	6	
	One time filling explosive with multiple blasting	2	
	Connecting blasting bus bar to wires directly	4	
	Blasting with the wires exposed to air	6	
Electromechanical equipment without explosion resistance	Cable breakage or bare cable joint	13	25
	Coal electric drill without explosion resistance	8	
	Junction box without explosion resistance	3	
	Signal device of hoist without explosion resistance	2	
	Scraper conveyer without explosion resistance	2	
	Local fan without explosion resistance	1	
	Short circuit of trolley wire resulting in spark	3	
Open fire	Smoking	4	7
	Fire without an extinguisher in fire area	2	
	Illumination by open fire	3	
Illegal cap lamp operation	Dismantling cap lamp	7	9
	Cap-lamp without explosion resistance	4	
Strike spark	Metal strike spark	7	7
	Rock strike spark	2	
Friction spark	Metal friction spark	2	3
	Machine friction	2	
Spontaneous combustion	Spontaneous coal combustion	6	8
	Spontaneous coal combustion resulting in fire	4	
Maintenance of powered electromechanical equipment	Maintenance of powered coal electric drill	4	6
	Maintenance of powered scraper conveyer	1	
	Maintenance of powered illuminated signal device	1	
	Maintenance of powered junction box	1	

4.2 Operating locations

In theory, as long as an underground coal mine has the three necessary conditions to trigger a gas explosion, ESGEAs could occur at any location. However, location does play a critical role in the ESGEA occurrence. Fig. 2 presents the distribution of the ESGEA locations at different accident sites in Chinese coal mines. Of the 19 locations (Fig. 2), the heading face is the most frequent location of ESGEA occurrence (44 accidents), followed by the coal face (35 accidents) and return airway (8 accidents), accounting for 35%, 28% and 6% of the total accidents, respectively. The heading face and coal face are the primary production locations in underground coal mines, which are more likely to be the locations of unsafe behaviors and electromechanical equipment leading to ESGEAs. For example, miners usually use a coal electric drill that is not explosion resistant to drill the blast hole in the heading face. Moreover, blasting is widely used at the heading faces and coal faces in Chinese coal mines. It is noteworthy that an inadequate sealed hole, an inadequate resistance line, the absence of a water stem, bulldozing and blasting with the wires exposed to air are the four major types of illegal blasting in the heading face and coal face. Once a human error is made during the course of blasting, such as an inadequate sealed hole, the ignition of ESGEAs can be triggered.

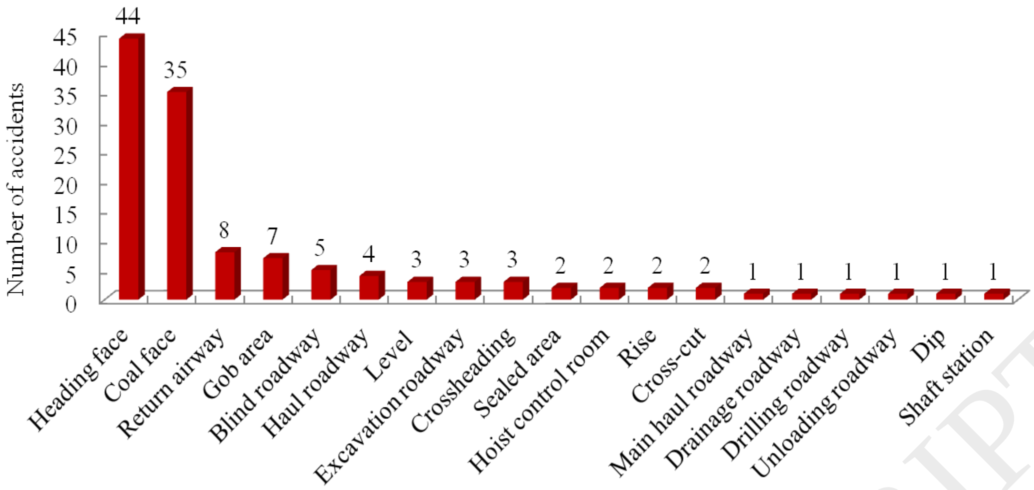


Fig. 2. Frequency distribution of ESGEAs by operation location

4.3 Accident time

Fig. 3 shows the historical occurrences of ESGEAs from 1950 to 2015 and indicates that the ESGEA occurrence frequency has a downward tread. In general, the ESGEA occurrence frequency and death toll since 1950 has passed through three phases: a stable period (1950-1989), an increasing period (1990-2005), and a decreasing period (2006-2015). The number of accidents and death toll during the three periods are shown in Table 7. In the stable period, coal consumption was low, as China was in the agricultural economy and early industrialization stage when it experienced a recession. Since 1990, coal production and consumption have continued to increase as China implements an Expanding Financial Policy by increasing infrastructure investments and advancing industrialization. On the other hand, the enforcement of laws and regulations, the construction of a supervision system and the improvement of safety technology and equipment have lagged behind the development of the coal industry, which is an important factor of the frequent

ESGEAs. In particular, ESGEA occurrences reached a peak period during 2000-2005, with 37 accidents and 2339 fatalities. Since then, the safety issue of gas explosions in Chinese coal mines has attracted great concern within the SACMS and Chinese government. Some countermeasures have been enacted and implemented since 2005. These countermeasures include the following regulations and policies:

- Coal Mine Safety Regulation;
- Special Regulation on the Prevention of Coal Mine Production Safety Accidents;
- Measures for Determining Hidden Dangers of Major Production Safety in Coal Mines;
- Coal Mine Production Safety Accident Report and Investigation Handling Regulation;
- Implement a coal mine closure policy with small-scale or unsafe production conditions

Although ESGEAs have been controlled effectively since 2006, catastrophic accidents have not been eliminated in Chinese coal mines.

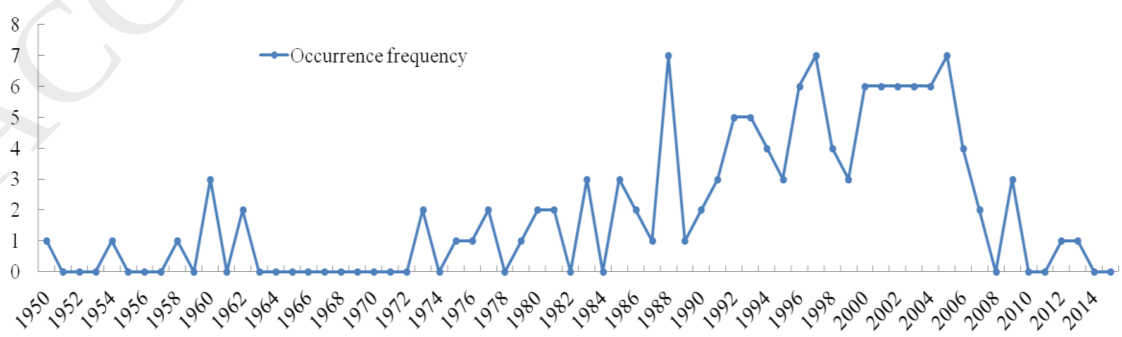


Fig. 5. Frequency distribution of ESGEAs at a yearly level

Table 7 Three periods of ESGEA occurrences

Year	Number of accidents	Number of accidents (a^{-1})	Deaths	Deaths (a^{-1})
1950-1989	36	0.9	2273	57
1990-2005	79	4.94	4712	295
2006-2015	11	1.1	517	52

Fig. 4 reveals the frequency distribution of ESGEAs by month in China. The month with the highest ESGEA occurrences was November with 20 accidents, followed by December with 16 accidents, while January and September have the fewest accidents of 6 and 4, respectively. This phenomenon may relate to the seasonal change in coal output. November and December are the last months in the year, and thus, there is pressure to accomplish the annual coal production target, which may neglect the safety requirements during production. Moreover, these periods are the cold winter season in northern China, and the hydropower supply decreases seasonally. This leads to increased coal consumption for direct heating and electricity generation. In addition, January has the fewest number of ESGEAs, as Spring Festival usually occurs in January when many coal mines are closed for the holiday.

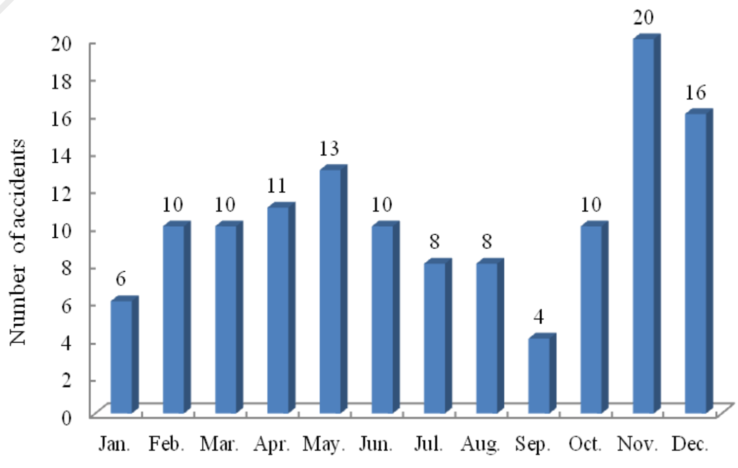


Fig. 4. Frequency distribution of ESGEAs at a monthly level

Fig. 5 indicates the frequency distribution of ESGEAs by the day of the week in Chinese coal mines. For the frequency of ESGEAs, the three highest days were Saturday (26), Monday (23) and Sunday (22), while Tuesday was lower than the other week days. This may be linked to the shift patterns in Chinese coal mines. Administrative staff and engineering technicians do not work on Saturday and Sunday, which may result in inadequate safety management. Moreover, miners were eager to finish work and take a break as soon as possible, which leads to the improper handling of potential accidents and insufficient shift-change briefings. Normally, there are three shifts a day, e.g., 0-8:00, 8:00-16:00 and 16:00-24:00, while most ESGEAs occurred during the shift between 8:00-16:00, as shown in Fig. 6. Among them, 10:00-12:00 has the highest frequency of ESGEAs, which accounts for 20 accidents and 16% of the total accidents. The major reason is probably due to peak production at this shift. Coal mines in China are labor intensive, so a larger number of miners enter underground to work, and the machines continue running at high speeds, which generates more hazards for ESGEAs. As a result, ESGEAs occurred more frequently from 8:00 to 16:00.

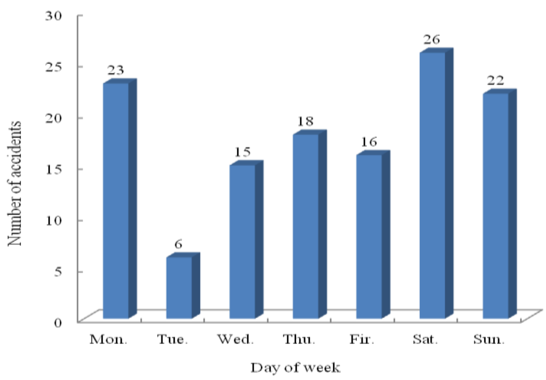


Fig. 5. Frequency distribution of ESGEAs at a daily level

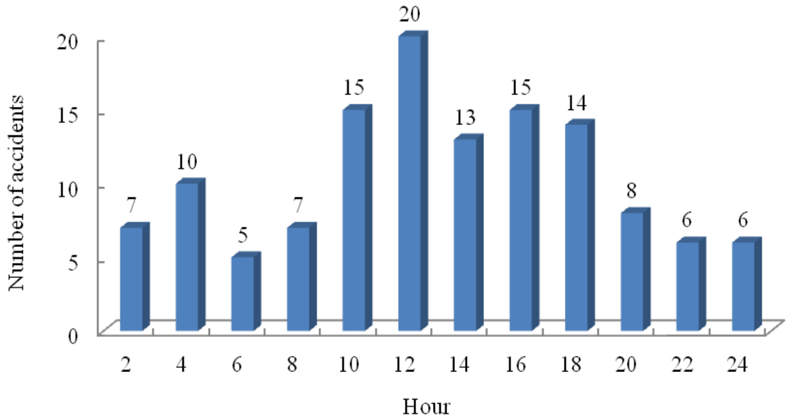


Fig. 6. Frequency distribution of ESGEAs at an hourly level

4.4 Accident Regions

In China's twenty-six coal-producing regions, ESGEAs have occurred in 19 provinces. The statistics data from 1950 to 2015 were normalized by the total hours worked (66 years) in order to compare the number of accidents and deaths among different regions, as shown in Figs. 7 a and b, respectively. Shanxi has the worst record of ESGEAs caused by 0.45 accidents and resulting in 23 deaths every year, followed by Henan (0.29 accidents and 21 deaths) and Heilongjiang (0.29 accidents and 15 deaths). This may be related to the coal reserves, coal output and the number of coal mines. For example, Shanxi's coal reserves and coal output account for approximately 25% and 27% of China's total quantity, respectively (SBCI, 2017). Though Shanxi has rich coal reserves, there are complex geological conditions and high gas contents that increase the difficulty of coal mining and the probability of gas explosion. Even worse, small coal mines with obsolete machines and technologies and poor safety management account for approximately 70% of the total (SBCI, 2017). In these coal mines, it is difficult to implement the measures for the collection and utilization of enterprise production safety funds, which severely restricts the application of new safety technology and advanced production equipment for gas treatment, as well as the improvement of the poor operation environment. In addition, most miners are migrant workers that usually violate the operating regulations and safety measures due to their minimal safety awareness and poor professional skills. Furthermore, coal mines are one of the major industries for the local economy and a major employer in Shanxi, Henan and Heilongjiang. Driven by their down economic interests, the local government and coal mine manager might neglect or violate the laws and regulations during the safety inspection process, which occurred frequently as the indirect cause of ESGEAs in the three provinces.

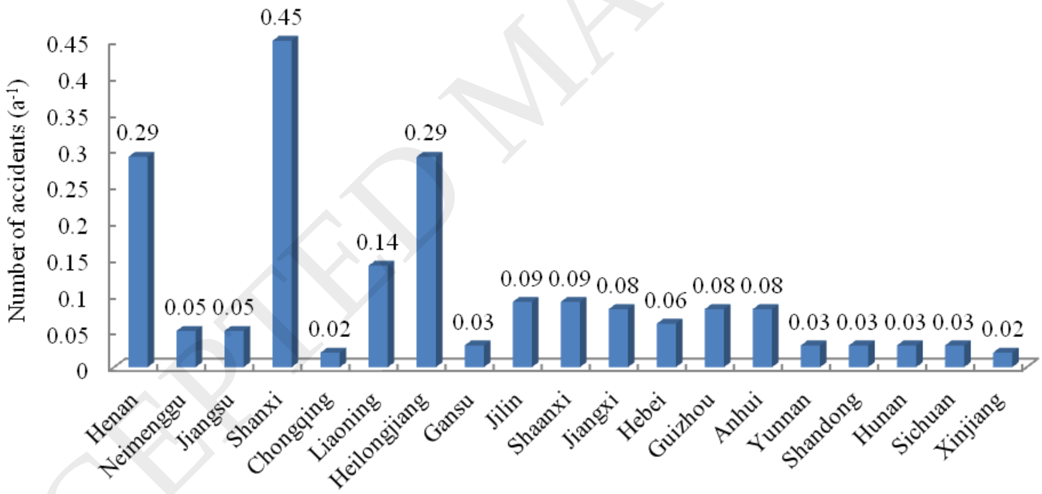
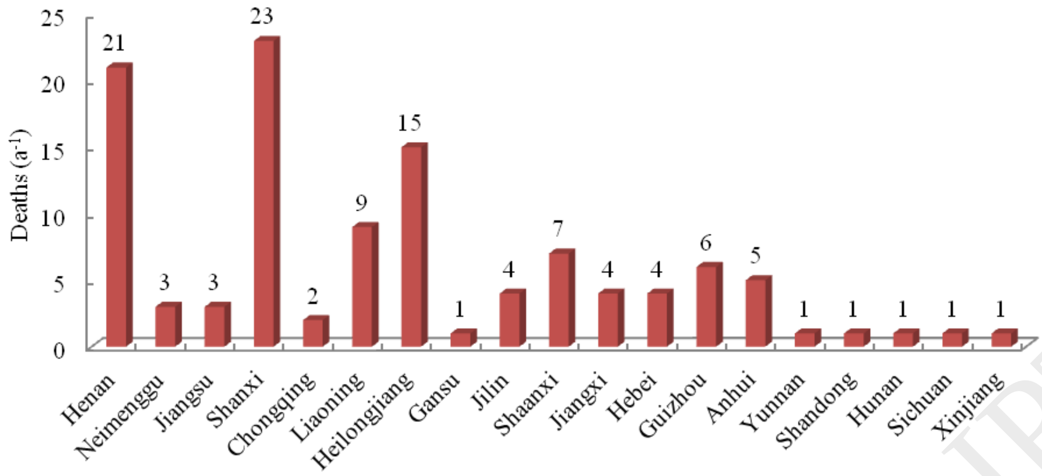


Fig. 7. (a) The annual number of ESGEAs in different regions



(b) The annual deaths in ESGEAs of different regions

4.5 Ownership of coal mine

According to the coal mine ownership, 126 coal mines with ESGEA occurrences are classified in Table 8. As shown in Table 8, there were 55 accidents and 3975 deaths in state-owned coal mines and 32 accidents and 1579 deaths in private-owned coal mines. State-owned coal mines have a large number of miners and rich coal resources with long periods of coal production, which contribute to most of the national output. Many state-owned coal mines usually attach importance to production regardless of safety issues in order to fulfill the annual production plan. In the meantime, the advanced technology and equipment of gas treatment may not be up to date. For private-owned coal mines, the main factor may be due to an inadequate safety investment and thus lack equipment and technology for gas detection. Furthermore, safety education and training may be more difficult to implement in private-owned coal mines due to the profit-driven environment.

Table 8 Ownership distribution statistics of ESGEAs

Ownership type	Number of	Percentage (%)	Deaths	Percentage (%)

	accidents			
State-owned	55	44	3975	53
Local state-owned	19	15	1093	15
Township-owned	15	12	676	9
Village-owned	5	4	179	2
Private-owned	32	25	1579	21
Sum	126	100	7502	100

5. Countermeasures

From the above analyses on ESGEAs, the following suggestions can be made to prevent gas explosion accidents in China.

(1) Comprehensive coal mine safety legislation

At present, the coal mine law system and safety management process are based on the "Coal Act", "Mine Safety Act", "Coal Mine Safety Supervision Regulation", and "Accidents Reporting and Investigation Regulation", which have yet to enact a coal mine-specific act for occupational health and safety in China. A Coal Mine Occupational Health and Safety Act should be enacted in China, which imposes requirements relating to safety and health management systems, emergency management systems, welfare systems, standard operating procedures, electrical activities, equipment and installations, violations, mine plans and other issues. The Coal Mine Occupational Health and Safety Act can play an important role in achieving occupational health and safety goals. On the one hand, the Coal Mine Occupational Health and Safety Act will establish permanent mandatory health and safety standards that protect the health and safety of miners and provide the legal grounds for preventing violations of major disasters (e.g., gas explosion, inundation or dust explosion). On the other hand, the Coal Mine Occupational Health and Safety Act will not only bring the laggard coal enterprises up to a minimum legal standard but also encourage the investment in more safety equipment and facilities, research programs and training plans aimed at preventing major disasters and occupational diseases.

(2) Optimizing the energy consumption structure

China's energy reserves are rich in coal and low in oil and gas, making coal one of China's main energy sources. For example, in 2015, China's coal, petroleum and hydroelectric consumption accounted for 64%, 19% and 9% of the total energy consumption, respectively, while renewable energy, such as wind, nuclear, and solar power, only accounted for 9% (NEA, 2017). In the US, petroleum, natural gas and coal consumption account for 36%, 29% and 16% of the total energy consumption, respectively, while renewable energy accounted for 19%. Based on the energy structure, the US has developed a more sustainable energy structure than China. Therefore, there is much room for China to adjust its energy structure and to promote the use of petroleum, natural gas and renewable energy to reduce coal consumption. In addition, the Chinese government should encourage energy companies to develop new energy technology and equipment and close down coal mines with risky production conditions and frequent accidents. This is vital to improve energy efficiency and to control coal mine accidents, especially ESGEAs.

(3) Establishing a nongovernmental supervision system

At present, the SACMS and the Coal Industry Bureau of local governments are responsible for the safety supervision of coal mine production in China. In some cases, the administrators of the SACMS and Coal Industry Bureau accept bribes from production safety violators or hold ownership stakes in illegal private coal mines. The labor unions of coal mines have no rights in the decision making and supervision for production safety at mines, which are mainly responsible for the calculation and payment of miners' welfare. The key is that sources of economic and personnel appointments for the labor unions of coal mines have to be implemented for coal enterprises. Unless miners are permitted to establish completely independent labor unions and miner safety committees, the safety of miners in coal production cannot be effectively enforced. Insurance companies are reluctant to enter into the coal industry because of the high risk. The coal industry has not set up a nongovernmental safety supervisory body in China. Thus, labor unions and insurance companies can be established as the nongovernmental supervisor system for coal mine inspection. Labor unions should be granted independent supervision rights through legislation rather than merely the right to provide suggestions in terms of coal mine production safety. For example, the United Mine Workers of America (UMWA) usually sues the Mine Safety and Health Administration (MSHA) or other governmental agencies for failure to enforce safety laws or otherwise abide by the law, and they can even lobby in parliament to pass mining laws (Homer, 2009). Hence, a powerful labor union becomes an enforcer of the laws and can enable miners to exercise their legal rights to refuse dangerous work tasks, report safety violations by the coal enterprise or individuals, and advocate or participate in the enacted laws. In addition, the state can issue a policy to guide and support the insurance companies into the coal industry in order to promote safety and an insurance system.

(4) Developing a disaster simulation system

In China, a disaster simulation system is seldom used in coal mines. Meanwhile, the existing disaster simulation system has large gaps in the mining process simulation, monitoring and schedule, disaster warning and emergency rescue decision. The popularity level and poor performance of the disaster simulation system is one fundamental cause that restricts disaster prevention and resilience in Chinese coal mines. Thus, a high-performance disaster simulation system should be developed to enhance the predictability of potential accident hazards and the precontrol level of gas explosion risks. A high-performance disaster simulation system can construct a 3D visual dynamic model and an accident evolution model that implement the dynamic simulation and nonlinear analysis of the mining environment, mining-induced stress, equipment parameters, engineering parameters, process flow and action parameters. On this basis, the disaster simulation system can analyze the various disasters (e.g., gas explosion, coal and gas outburst, fire, coal dust explosion and mine inundation) under different geological conditions, mining methods and mining technology to provide the scientific foundation and technical support for hazard inspections, disaster forecasts, disaster control and emergency decisions. It is a vital method to prevent gas explosions and develop a rescue plan.

(5) Increasing the level of mechanization and automation mining

Most Chinese underground coal mines usually have complex geological conditions (e.g., abundant mine water, high geo-stress and high gas content), a low level of mechanization and automation and a large number of miners, which are indirect causes of gas explosions resulting in a large number of casualties. Thus, Chinese coal mines should increase the level of mechanization and automation in mining operations in order to decrease the number of miners and increase production efficiency. In addition, due to the lack of investments in production equipment and safety facilities, the low level of mechanization and automation in private-owned coal mines and small coal mines should be improved in China. Moreover, as flames from blasting were the most prominent ignition sources of ESGEAs, a high level of mechanization and automation in mining is an effective way to avoid blast mining in Chinese coal mines. Finally, intelligent-unmanned mining should be actively studied to focus on intelligent mining equipment, dynamic data capture and analysis, and an ultramodern mining scheduling system (Wu et al., 2012), which are helpful to prevent coal mine accidents and occupational diseases for miners, especially ESGEAs.

(6) Strengthening safety management and checking key equipment

Statistical analysis of ESGEA data has shown that risky behaviors by miners may be the key cause of the gas accumulation and ignition sources of ESGEAs. Hence, coal enterprises should invest more equipment and time in safety education and training so that miners can establish good safety awareness and operational habits. For example, computer simulation technology can be used for the risk assessment of gas explosions and to develop a rescue plan, and virtual reality technology can be applied to train miners by improving their occupational skills and emergency awareness. At the same time, coal enterprises can set up and implement an effective system of rewards and penalties for safe and unsafe behaviors, respectively. Furthermore, coal enterprises must effectively manage key equipment in this regard, especially checking and maintaining local fans, ventilation ducts, blast devices, and coal electric drills. The procedure to handle cable and wire should be normalized during the coal mine production process. Finally, risk management should be introduced as legislative requirements in Chinese coal mine. To prevent gas explosions in coal mines, it is vital to increase risk management and carry out risk control effectively. The risk management procedure for gas explosions must include risk standards, hazard identification, hazard analysis, risk estimation, risk evaluation, major risk management plan, safety countermeasures and optimization. For the safety checks to prevent gas explosion, in addition to the conventional gas safety inspection system during the day, an enhanced safety inspection system is essential in November and December and during the weekends for the prevention of ESGEAs.

6. Conclusions

ESGEAs are not rare in Chinese coal mines and have resulted in a large number of fatalities and substantial property damage. However, to date, there is no study in the literature on the ESGEAs that have occurred in Chinese coal mines. The patterns and characteristics of ESGEA accidents should be analyzed. Therefore, this study is attempting to initiate this analysis. Some statistical conclusions that are useful for preventing ESGEAs are summarized as follows:

(1) Disorganized ventilation fan management was the most frequent cause of gas accumulation in ESGEAs, while illegal blasting was the most prominent cause of ignition sources in ESGEAs. Improving the management of the ventilation equipment and blasting procedure is crucial to prevent ESGEAs.

(2) The heading face and coal face are the most frequent operation locations where ESGEAs occur in Chinese coal mines. Enhancing the safety inspection level at these locations can effectively reduce the number of ESGEAs and fatalities.

(3) November, December and weekends have the highest possibility of ESGEA occurrences in Chinese coal mines. A special safety inspection system should be strictly enforced during these periods to prevent ESGEAs.

(4) Shanxi has the worst records of ESGEAs, followed by Henan and Heilongjiang. Increased governmental supervision and effective measures for gas treatment should be implemented to prevent ESGEAs in these three provinces.

(5) State-owned coal mines have the highest frequency and death toll for ESGEAs, followed by private-owned coal mines. State-owned coal mines and private-owned coal mines should be the main targets for supervision to preven ESGEAs.

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