Journal of Rock Mechanics and Geotechnical Engineering 8 (2016) 423–442

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Review

Safety risk management of underground engineering in China: Progress, challenges and strategies

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ARTICLE INFO

Article history:
Received 4 December 2015
Received in revised form
31 March 2016
Accepted 13 April 2016
Available online 20 May 2016

Keywords:
Underground engineering
Safety risk management
Safety behaviors
Safety challenges
Safety progress and strategies

ABSTRACT

Underground construction in China is featured by large scale, high speed, long construction period, complex operation and frustrating situations regarding project safety. Various accidents have been reported from time to time, resulting in serious social impact and huge economic loss. This paper presents the main progress in the safety risk management of underground engineering in China over the last decade, i.e. (1) establishment of laws and regulations for safety risk management of underground engineering, (2) implementation of the safety risk management plan, (3) establishment of decision support system for risk management and early-warning based on information technology, and (4) strengthening the study on safety risk management, prediction and prevention. Based on the analysis of the typical accidents in China in the last decade, the new challenges in the safety risk management for underground engineering are identified as follows: (1) control of unsafe human behaviors; (2) technological innovation in safety risk management; and (3) design of safety risk management regulations. Finally, the strategies for safety risk management of underground engineering in China are proposed in six aspects, i.e. the safety risk management system and policy, law, administration, economy, education and technology.

1. Introduction

Underground construction is in a great demand in many civil and infrastructure projects all over the world, such as metro (Zhong et al., 2003) and hydropower projects (Lin et al., 2015a). In the last decade, tunnel construction has presented a powerful momentum for rapid economic development. However, owing to various risk factors associated with complex project environments, violations of safety rule occur frequently in tunnel construction, resulting in serious problems in the related project operation (Liu et al., 2005; Qian and Rong, 2008; Qian, 2014; Wu et al., 2015). On 6 July 2010, a tunnel collapse took place in Prague, Czech Republic, causing a 15-m-wide sunken pit on the ground surface (Thomas, 2010). On 23 August 2012, water leakage in metro line caused chaos in Warsaw, Poland (Waltz, 2012). Water flooded into the tunnel at the planned power station, causing considerable transportation problems in the already gridlocked city. Despite the rapid development of construction industry in China, which reached about 2200 billion US dollars in 2012, many problems with regard to the cost and safety risk management are observed (Wu et al., 2015).

In China, the number of construction accidents shows a rising trend in tunnel projects over the past decade. In general, there arises a public concern that tunnel construction may generate ground deformations (Ou et al., 2008; Yoo and Lee, 2008), which may affect the safety of surface buildings and road traffics, and lead to unacceptable damages. Statistics have shown that no significant improvement has been made in safety risk management of tunnel construction from 2008 to 2011. Analysis of accident records indicates that the liability accidents account for the majority of accidents in civil engineering, and the reasons for these accidents vary in different projects. With regard to the tunnel engineering, 60% of accidents occur due to both subjective and objective causes, 30% of accidents are liability accidents and 10% are completely triggered by objective causes. The causes for most liability accidents are similar in nature, including poor technologies, management and performance on hazard rectification. The objective causes for accidents in the tunnel engineering include adverse hydrogeological conditions, groundwater or heavy rainfall, and soft soil layers. Collapse is the most dominant accident type in the tunnel engineering, accounting for 60% of the total accident records. For

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.04.001

example, on 15 November 2008, a fatal tunnel collapse occurred one year after construction of Hangzhou metro line #1, resulting in 12 lives loss. The tunnel section affected by the collapse is 100 m long by 50 m wide, and the depth of the crater is 6 m. Water inrush and object strike are the second and third causes, respectively. In addition, explosion, pipeline damage and rockburst are also the common causes for accidents in underground engineering. The injury and death rates vary among different types of accidents.

Safety risk management has been intensively studied in the USA and Europe (Duddeck, 1996). In 1992, the Council of European Community published the Council Directive 92/57/EEC on the implementation of minimum safety and health requirements at temporary or mobile construction sites (The Council of the European Communities, 1992). In 2004, the working group of International Tunneling Association proposed its guidelines for tunneling risk management (Eskesen et al., 2004). In 2006, the International Tunneling Insurance Group issued a code of practice for risk management of tunnel works (ITIG, 2006). The Chinese government has also paid special attention to risk management of underground construction. In 2003, the Ministry of Housing and Urban-Rural Development (MOHURD) of China, together with eight relevant ministries, issued the advice on further enhancement of subway engineering management, proposing detailed requirements of safety risk management in the planning, design, construction, and operation of subway engineering. Recently, the MOHURD of China has issued the principle of risk control and the guideline of risk management for construction of underground works, which promote the standardization of safety risk management of underground engineering in China.

To avoid heavy casualties and property losses caused by safety violations, numerous studies have introduced risk-based analysis to safety prevention and control, which can be divided into qualitative and quantitative risk analyses (Smith et al., 2009). The former includes fault tree analysis (FTA), comprehensive fuzzy evaluation method (CFEM), safety check list (SCL) and the others, while the latter includes the job risk analysis method, influence diagrams, neural network (NN), support vector machine (SVM), decision trees and others. The above risk-based analysis methods have made significant contributions to safety risk management in complex engineering projects (Alfredo, 2002; Piniella et al., 2009). However, they are limited to static control and management (Alaeddini and Dogan, 2011). Khakzad et al. (2011) described FTA unsuitable for complex problems due to its limitation in explicitly representing the dependencies of events, updating probabilities, and coping with uncertainties. When the associated parameters, such as geological, design and construction parameters are changed, the aforementioned methods cannot accurately depict the updated feature of dynamic environments as the construction progress continues. Nor can professional supports or suggestions be provided in real time as the parameters are not updated.

In order to address the challenges presented by underground construction projects, studies are also conducted benefitting from new technologies, tools and approaches for construction safety management, including the above-mentioned analytical methods. Structural health monitoring (SHM) system, a comprehensive instrumentation of structures and environment, is widely recognized as a crucial element of underground construction safety management (Bhalla et al., 2005). For example, in Italy, the GeoDATA Company developed an information management system, namely the Geodata Master System (GDMS), which aims at risk management in underground engineering. Based on the geographic information system (GIS) and web technologies, the GDMS provides five sub-systems, including the building condition system (BCS), the building risk assessment (BRA) system, tunnel-boring-machine data management (TDM) system, monitoring data management (MDM) system and document management system (DMS). The GDMS provides complete risk management plans, and has been widely used in subway construction projects in Russia and Italy. However, the GDMS is not suitable for underground construction in China, due to the differences in monitoring technologies and construction management regulations.

The SHM system is intended to predict structural and environmental instability risks, which are frequently encountered in underground construction (Bhalla et al., 2005; Chai et al., 2011; Lin et al., 2014). By installing durable and robust sensors, it becomes feasible to automatically and intelligently monitor and predict the behaviors of underground structures in real time (Khoury and Kamat, 2009). Substantial work has been carried out on investigating the tracking technologies and their applications which can meet various requirements in underground construction practices (Lin et al., 2014). These proactive approaches could be used for dynamic identification and prevention of human error and behavior risks in underground construction. To date, several tracking technologies have been demonstrated as follows: radio frequency identification device (RFID) (Khoury and Kamat, 2009; Tu et al., 2009; Seco et al., 2010; Rao and Chandran, 2013), global positioning system (GPS), wireless local area network (WLAN or WiFi) (Jiang et al., 2015), ultra-wide band (UWB) (Carbonari et al., 2011), ZigBee, and indoor GPS (Ergen et al., 2007). These technologies are able to cover a wide range of area and give relatively accurate results (Behzadan et al., 2008).

In this paper, the main progress of the safety risk management of underground engineering in China in the past decade is first presented. Based on the analysis of the major accidents of underground engineering in the recent decade, the new challenges of the safety risk control are analyzed. The new strategies of safety risk management in underground construction are proposed in six aspects, i.e. the management system and policy, the legal, administrative, economic, educational and technical countermeasures. The structure flowchart of this study is illustrated in Fig. 1.

2. Progress in safety risk management

Qian and Rong (2008) and Qian (2014) proposed four suggestions specific to safety risk management of underground engineering in China:

(1) The laws and regulations of underground engineering should be improved.
(2) The safety risk management plans should be implemented in construction management of underground projects.
(3) Information technology should be employed to implement early-warning and decision-making support functions for safety risk management.
(4) More resources should be invested into researches on safety risk management, prediction and prevention of major accidents.

Over the past decade, tremendous efforts have been made to the safety risk management of underground engineering in China, including safety risk control regulations, management plans and related technologies. By taking into account the experts' opinions, the guides by researchers and government agencies, a sound safety risk management system has been established on the basis of technology, management, culture, regulations and other means.

2.1. Establishment of laws and regulations

In recent years, Chinese government has paid much attention to the laws and regulations of safety risk management for

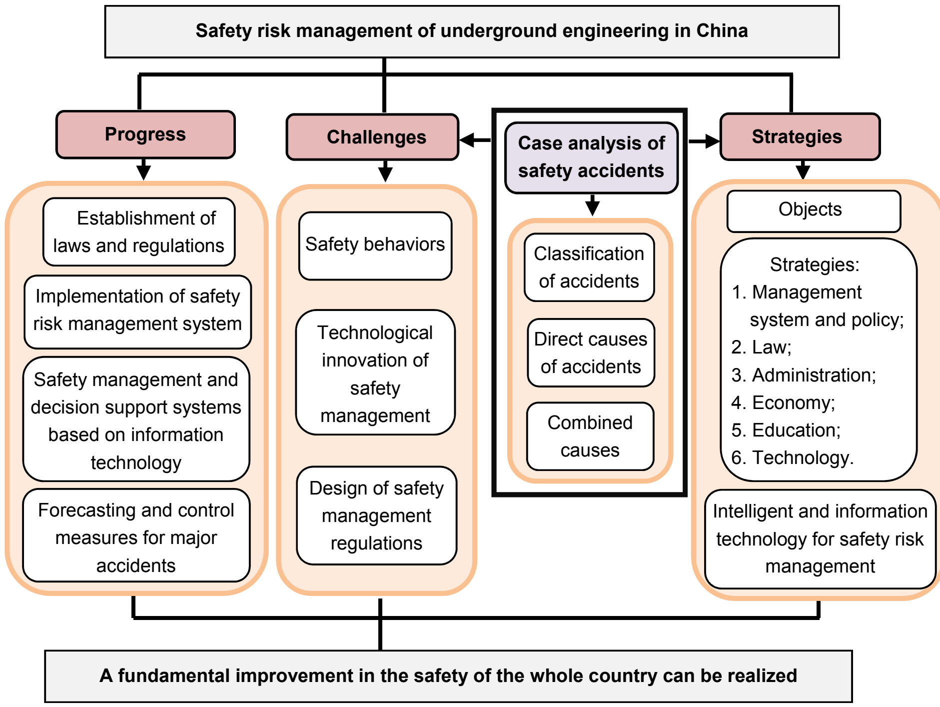

Fig. 1. The structure flowchart of this study.

underground construction. The law and regulation system of safety risk management in China is a combination of several laws, regulations and technical standards (Fig. 2), which can be divided into four levels and nine classes as follows: (1) The law level: the law class; (2) The statue level: the administrative statute class and the local statute class; (3) The regulation level: the ministry regulation class and the local government regulation class; (4) The standard level: the national standard class, the industrial standard class, the local standard class and the company standard class. In general, the law and regulation system of safety risk management for underground construction in China is implemented based on the Constitution, the Construction Law and the Production Safety Law. Issued by administrative regulations, including "Regulations on production safety management for construction projects" and "Regulations on safe production license", and supported by ministerial regulations, including "Administrative regulations of safe production for construction projects" and "Regulations of safe production license for construction enterprises", the system includes a large number of local statutes, regulations and standards. The main progress in establishment of laws and regulations in the recent decade can be summarized as follows:

(1) With regard to the construction of the urban subway system, the MOHURD of China issued "Temporary regulations on safety and quality management of urban rail transit projects" in January 2010. It provides explicit provisions on risk assessment, risk monitoring and emergency disposal, and stresses that "safety and quality risk management has to be strengthened throughout construction of urban rail transit projects". It clearly defines the responsibilities of all parties participating in urban rail transit construction. For example, the project owner is required to assess the safety and quality risks and organize expert argumentation at the preliminary design stage. Meanwhile, specific evaluations by experts on seismic resistance and wind resistance are also necessary. The costs of risk assessment, field monitoring and environment investigation should be included in the budget. Geological risks should be specified in the geological survey stage. Guidelines on survey of special geological conditions should be prepared in advance if necessary. The design institutions should organize expert argumentation on the design scheme, monitoring and control standards for the environment, if high risks are expected. Meanwhile, a series of relevant regulations, including "Regulations of safety and quality contingency plan management for urban rail transit", has been issued. The MOHURD of China also issued "Specifications on underground construction risk management for urban rail transit" in 2011, in order to regulate the technical details for risk management.

(2) With regard to railway construction, "Temporary regulations of safety risk management for railway construction" was issued in September 2010. The regulation extends risk management from tunnel engineering to all kinds of railway projects. In 2014, China Railway Corporation (originated from Ministry of Railways) issued "Technical specifications of risk management for railway construction".

(3) With regard to traffic engineering, the Ministry of Transport of China issued "Guide for safety risk assessment of highway bridge and tunnel design" in 2010 and "Guide for safety risk assessment of highway bridge and tunnel construction" in 2011. On this basis, the policies on risk assessment have been established. The guides provide detailed and feasible methods for evaluating common risks in highway bridge and tunnel construction.

A legal system of safety risk management covering multiple levels of laws, statutes, regulations, and industrial standards has been established in China. However, many challenges are observed in implementation of the legal system.

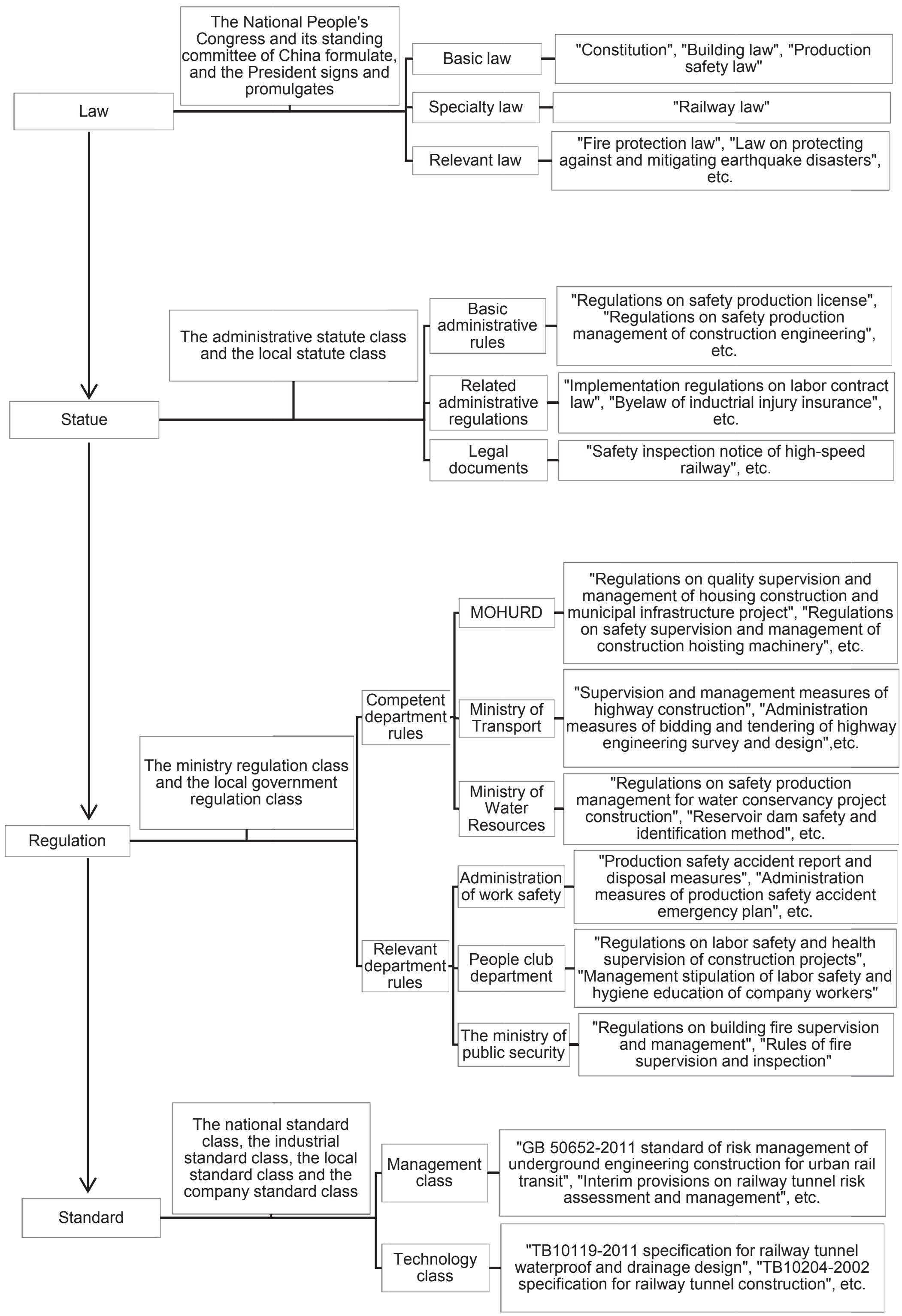

Fig. 2. The legal system for safety risk management of underground construction in China.

2.2. Implementation of safety risk management system

Great efforts have been devoted to establish the safety risk management system for underground construction in China in five aspects, including the organization structure system, the safety culture system, the technical management system, the disaster prevention and early-warning system, and the project insurance system.

For construction of urban transit, the safety risk management has been used in construction of metro lines in Beijing, Shanghai, Guangzhou, Shenzhen, Nanjing, Chengdu and other cities in China. The safety risk management systems suitable for local conditions have been gradually established over years. For example, "Safety Risk Management System for Construction of Urban Transit" has been issued in Beijing, which covers engineering survey, design, construction and post-construction phases (Fig. 3). In summary, the safety risk management system of urban transit construction in China has the following characteristics:

(1) Technical management and risk control during the entire construction process: Risks should be identified in the planning and survey stages. Risk sources shall be avoided or mitigated in the design stage. Attention shall be paid to risk control and management during the construction stage. Risk assessment and tracking should be strengthened in the post-construction phase. The third-party supervision should be adopted to reinforce the quality management of technical works at all stages.
(2) Risk assessment, control and prevention of risk sources: Safety risk assessment and hierarchical control system should be generally implemented. Through safety risk identification, risk assessment, hierarchical control and expert checks in advance, safety risk can be mitigated or roughly eliminated. Meanwhile, management measures should be reinforced for potential risks and contingency plans should be drawn to ensure that risks are under control.
(3) Implementation of safety responsibility of each party involved: Proper contracting strategies regarding reward and punishment shall be implemented to reinforce the safety responsibilities of all parties involved in underground construction.
(4) Process monitoring: Managers should pay attention to on-site behaviors during construction. Dynamic management should be strengthened by refined, informationized and programmed means. Process monitoring and control, supervision measures and behavior norms shall be implemented effectively.

Based on the third-party monitoring, real-time tracking of various hazard sources can be realized. Based on the conditional acceptance of key points before construction, major risks are effectively controlled. Site inspection is used to control safety hazards dynamically. By introducing information technology into monitoring, the efficiency of risk management is improved. Based on the integrated design, construction and management, a linkage mechanism is formed to promote the capability of safety protection. With the hierarchical early-warning management, proper and efficient treatment measures are selected.

2.3. Safety risk management and decision support systems based on information technology

In recent years, significant progress has been made in risk management and early-warning decision support system of underground construction in China by adopting information technology. Sun (1999) studied the intelligent prediction and control of urban underground construction safety and its three-dimensional (3D) simulation system. Lin et al. (2013, 2014) and Jiang et al. (2015) employed several information technologies, including WiFi, 3G, GPS and RFID to establish a risk identification and management system for large-scale hydropower projects. With this system, real-time tracking of site staff and workers can be realized. Together with the construction market and personnel management system, online monitoring of personnel access and activity tracking, early-warning, prediction and evaluation analysis can be implemented. The system promotes site performance analysis and rapid response to quality and safety management, and all-around safety management can be achieved. For instance, a real-time tracking system for personnel safety in the construction area was established for Xiluodu hydropower project on the Jinsha River, China (Fig. 4) (Lin et al., 2014). The 3G technology was adopted for data transmission, GPS auxiliary positioning technique for the deck, and the WiFi-based positioning technique for corridors. Smart phones with multiple sensors were employed as the major devices to monitor site personnel. Highly accurate real-time positioning, safety assessment analysis of site personnel, 3G communication dispatching, early-warning and messaging were realized. By mining massive data collected by the system, valuable information can be derived. Such information can satisfy the requirements of the owner and the superintendent on labor force consumption and analysis and management of safety behaviors. With the above devices and networks, the system can be extended to safety management, video monitoring, multiple-sensor internet of

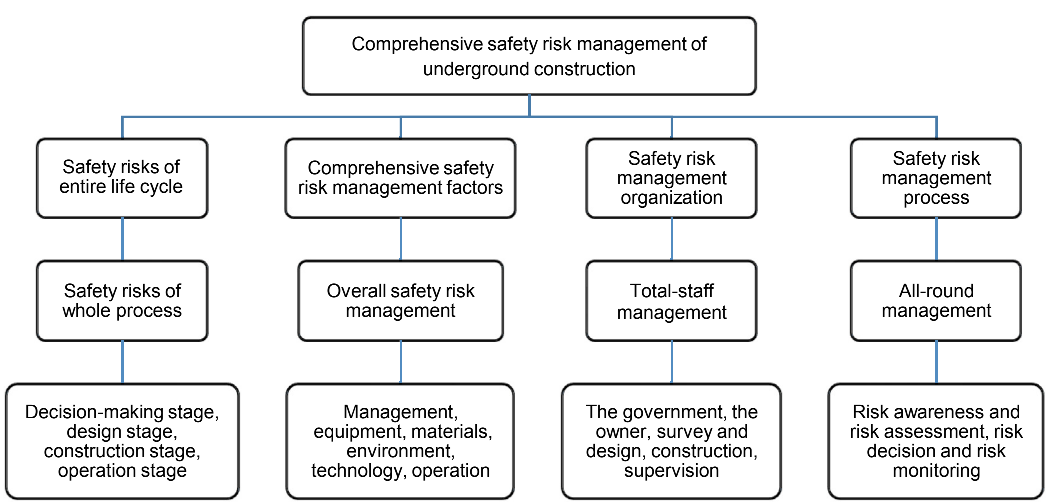

Fig. 3. The safety risk management system of underground construction in China.

Fig. 4. Location based services (LBS) web client interface on dam construction site (Lin et al., 2014).

things and construction machinery management. Scientific allocation and integrated management of personnel, resources, environment and regulations can also be achieved.

2.4. Safety risk management, forecasting and control measures for major accidents in underground engineering

In recent years, in order to enhance the safety risk management in underground construction, great achievements have been made in major accident forecasting and prevention in China, for instance, monitoring and forecasting techniques for water and mud inrush, and rockburst (Li et al., 2013a,b), the risk management and control over the entire construction process of metro projects (Zhong et al., 2008; Shi et al., 2012), and forecasting of rockbursts based on microseismic monitoring (Tang et al., 2011; Ma et al., 2015; Xu et al., 2016).

(1) Monitoring and forecasting techniques for water and mud inrush

Water or mud inrush is predictable based on some precursory information. In order to prevent and avoid water or mud inrush, advanced geological forecast has to be performed. Due to the complexity of geological condition and multiple explanations of geophysical detection results, single forecasting method can hardly ensure accurate and reliable results. Different forecasting methods may give different results for the same event and they are sensitive to different events. Therefore, in order to improve the accuracy and precision of forecasting, integrated advanced geological forecasting methods are needed, including macroscopic advanced geological forecast (engineering geological method), long-distance (200–500 m) advanced geological forecast (engineering geological method, TSP detection), short-distance (within 50 m) advanced geological forecast (geological radar, infrared detection for groundwater, transient electromagnetic method, advanced drilling, pilot tunnel and empirical methods). The research group led by Professor Li established a four-stage whole-process monitoring and forecasting system for water inrush hazards during tunnel construction (Fig. 5), based on a great number of engineering practices and multiple geophysical detection methods (Li et al., 2013a,b). The system stresses the importance of geological analysis and takes advantages of seismic prospecting, transient electromagnetic and induced polarization (IP) methods. The system has greatly improved the prediction precision and efficiency for water inrush hazards, and provides effective measures for problems caused by water inrush. The system has been applied to many tunnel projects in China.

(2) Prediction of rockbursts based on microseismic monitoring

The laws of microcrack initiation, propagation and coalescence are the evolution characteristics of macroscopic rockburst, which are also the theoretical basis for monitoring and forecasting of rockburst (Tang et al., 2011; Ma et al., 2015; Xu et al., 2016). The P- and S-waves generated by microcracking can be captured by geophones or accelerometers, and these signals are then transformed into digital data signals and processed by data processing software. The time, location and intensity of microseismic events can be determined. Ultimately, the rockburst proneness, and qualitative and quantitative assessment of the location and magnitude of rockbursts can be analyzed according to the evolution of microcracks. The microseismic monitoring technique has the following characteristics:

(i) The monitoring scope can be very large. The time, location and magnitude of microcracking events in the rock mass can be determined directly. It overcomes the drawbacks of the traditional “point” monitoring techniques which are localized, discontinuous and labor-intensive. Microseismic monitoring represents the trend of stability monitoring for rock structures.
(ii) The monitoring system is automatic and intelligent, which supports remote information transmission. The monitoring instruments are being developed towards highly integrated, small-size, multi-channel and highly sensitive devices.
(iii) As the monitoring system receives the information of seismic waves, the sensors can be installed in the region far away

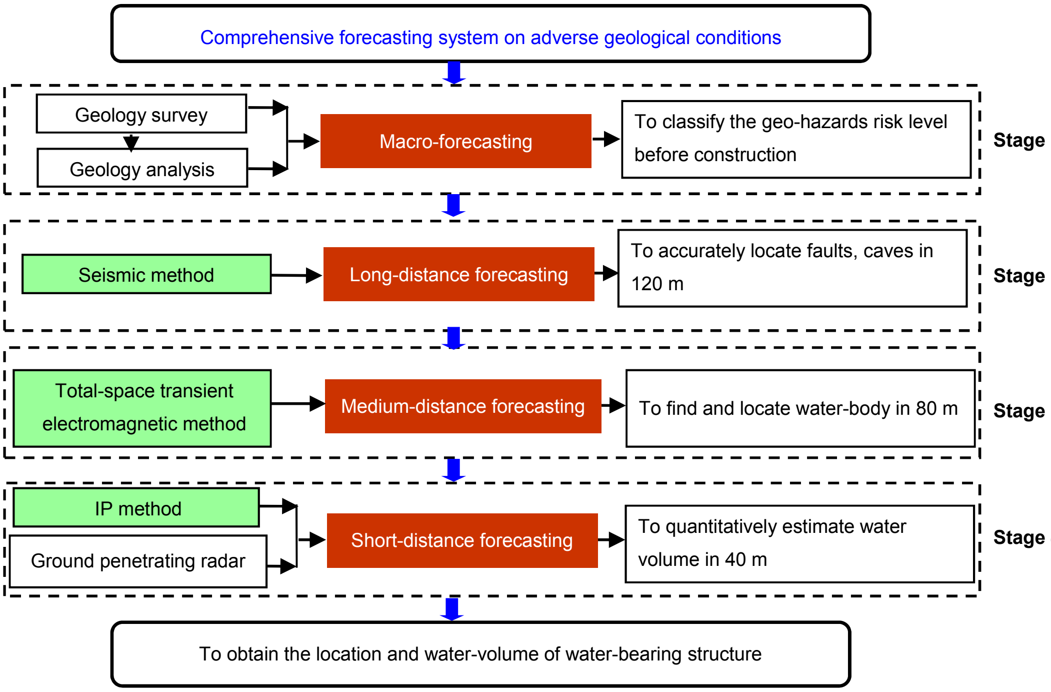

Fig. 5. Schematic diagram for comprehensive forecasting system on adverse geological conditions (Li et al., 2013a,b).

from the failure-prone area, which is advantageous for ensuring long-term operation of the monitoring system.

The research team led by Professor Tang carried out microseismic monitoring of rockbursts in the headrace tunnels at Jinping II hydropower station (Tang et al., 2011). Rockburst monitoring was performed at 10 working faces. The layout of the microseismic monitoring system is shown in Fig. 6. The monitoring data showed that the accuracy of rockburst forecasting was as high as 85.5%.

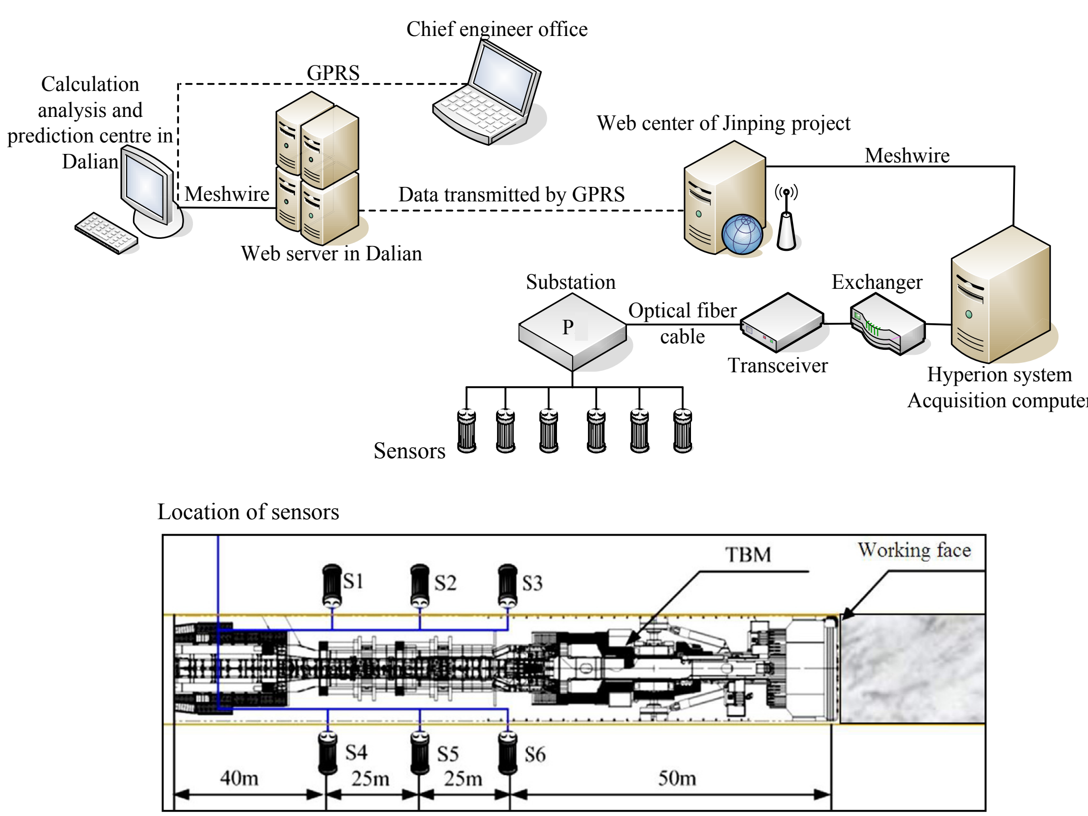

Fig. 6. Monitoring and analysis system for rockbursts during tunnel boring machine (TBM) tunneling for Jinping II hydropower station (Tang et al., 2011).

(3) Whole-process risk management and control techniques for metro projects.

On account of rapid development of metro projects in China, complex project planning, design, construction and operation, and requirements on safety performance, the research group led by Professor Zhong proposed a system of risk control theory and risk detection method for planning, design, construction, commissioning, trial operation and operation stages, by utilizing theoretical analyses, small-scale experiments, laboratory tests and full-scale field tests (Zhong et al., 2008; Shi et al., 2012). The system includes identification and assessment of hazard sources, simulation of fire hazards, visualized detection of passenger flow, modeling for stability of surrounding rock masses, hot smoke detection, cold slippery detection, simulation of evacuation plans, simulation of large passenger flow, risk early-warning, etc. With this theory, comprehensive risk prevention and control can be realized at the planning, design, construction and operation stages of a metro project. One national standard (GB/T50438-2007) and five industrial standards of production safety (AQ8004-2007, AQ8005-2007, AQ8007-2013, AQ/T9007-2011, AQ/T9002-2006) have been issued. The system has been adopted in design, construction and operation stages at more than 300 metro lines in over 30 cities in China.

3. Case analysis of safety accidents

The number of casualties in construction industry in China generally has declined over the past decade. However, the total number of casualties is still large (Fig. 7). According to the analysis in Section 2, despite great progress in four aspects, the safety risk management still faces great challenges with varying economic and engineering scale. Especially for underground construction, a number of safety risks still exist.

3.1. Classification of accidents

Compared to other accidents, the problems, such as safety awareness, safety education, poor safety responsibility, exist in tunnel accidents. In addition, because the hydrogeological conditions of underground tunnel projects are generally complex, a number of uncertain factors are encountered. Based on the typical accidents occurred in China in the past decade (Table 1), the accidents are classified into collapse, object strike, geological hazard, explosion and toxic gas poisoning (Fig. 8). These accidents have the following features:

(1) Collapse and object strike are the major accident types, accounting for 61% of the total accidents. Collapses may be caused by various factors, such as adverse geological and hydrological conditions, poor management, improper construction, etc. The geological disasters, such as water and mud inrush, cause a number of collapses, mainly the earth collapse and landslide. Collapses often result in a chain reaction. For example, the casualties due to object strike in Xianghu station of Hangzhou metro line #1 was in fact caused by the ground subsidence, due to over excavation in the foundation pit, severe defects existed in the support system, delay of erecting the steel bracing and casting the concrete cushion.
(2) The accidents caused by complex geological conditions account for about 21% of the total accidents. In the tunnel projects, soft soil strata, water and mud inrush are the dominant factors. During construction process, complex rock structure is the prominent factor for accidents. Some accidents are completely caused by geological disasters without any sign before failure. On the other hand, it also shows that the investigation and prevention of underground disasters need to be further improved. On 28 November 2009, during construction of the drainage tunnel at Jinping II hydropower station by TBM, an extremely strong rockburst occurred. The longitudinal range of rockburst was about 30 m, and the crater depth was around 8 m. A great amount of rock powder was released during the rockburst and spread over the tunnel for 10 min. The huge amount of energy released during the rockburst destroyed the support system instantaneously, causing a wide range of collapse on the crown and sidewalls of the tunnel. The TBM was partially buried, the main girder was broken, and eight workers were killed.
(3) Toxic gas poisoning, explosion and other accidents account for about 18% of the total accidents. Underground construction is generally carried out in narrow space, leading to higher probability of toxic gas poisoning and explosion.

3.2. Direct causes of accidents

Statistical analyses of the typical accidents (Table 1) indicate that the liability accidents account for about 90% among all the accidents. The direct causes are described as follows.

(1) Poor safety awareness, neglecting of accident precursors, and fluky psychology

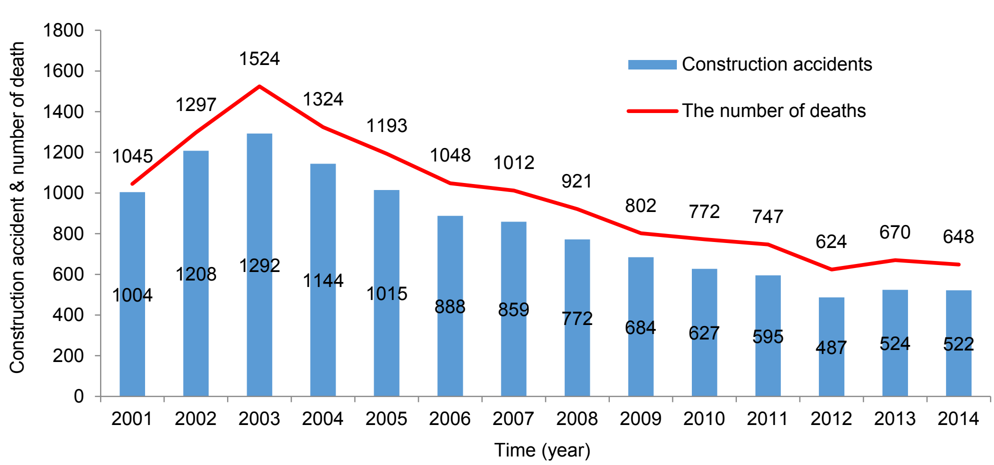

Fig. 7. Statistics of construction accidents and deaths in China from 2001 to 2014.

Table 1
Summary of major accidents in underground engineering in China since 2001.

No.	Accident	Type	Location	Date (MM/DD/YY)	Process	Consequence
1	Landslide of Nanjing metro line #2	Collapse	Nanjing, Jiangsu Province	5/28/2007	At 8:00 am, landslide occurred at east of west foundation pit of Chating station of metro line #2. The accident was located at the cross of Shuiximen street and east road of Jiangdong gate memorial.	2 deaths
2	Collapse accident at Suzhoujie station of Beijing metro line #10	Collapse	Beijing	3/28/2007	At 8:00 am, 1 m^3 of soil collapse was found between Section 10-10 and Section 6-6 at the southeast gateway of line #10. The vault was reinforced immediately. At 9:30 am, vault collapsed again during the repairing process.	6 deaths
3	Collapse accident at Shanghai rail transit line #4	Collapse	Shanghai	7/1/2003	At 6:00 am, a large amount of water and sand flooded into the operation face of passageway of Shanghai rail transit line #4, causing local damage of tunnel and ground subsidence in surrounding area. It resulted in severe inclination of 3 buildings and partial collapse of the flood control walls, which caused piping of the cofferdam.	The direct economic loss was 150 million Chinese yuan
4	Ground subsidence at Xianghu station of Hangzhou metro line #1	Collapse	Hangzhou, Zhejiang Province	11/15/2008	Ground subsidence occurred at Xianghu station of Hangzhou metro line #1, forming a cave-in with length of 75 m and depth of 15 m. Eleven cars fell down into the hole.	21 deaths, 24 injuries, and the direct economic loss was 49.62 million Chinese yuan
5	Collapse at Shanghai metro station	Collapse	Shanghai	8/20/2001	At 7:00 pm, 11 workers worked at the platform between axes 14 and 15 of the foundation pit. At 8:00 pm, landslide occurred at axis 16, burying 2 workers immediately. Two more workers were buried up to waist and other 6 rushed away from the pit. At 8:10 pm, the second slide occurred, with earth rushing from axes 18 to 12. The 2 workers were entirely buried and 16 steel bracing were broken.	4 deaths
6	Collapse between Hancheng road and Textile mall at phase I of Xi'an metro line #1	Collapse	Xi'an, Shaanxi Province	8/2/2009	At 1:00 to 5:00 am, the groove in the east section 20–35 m of Guanliang road, on the north side of the Sajinqiao bus station, was excavated. The groove was 4 m wide at the top, 3.5 m at the bottom and 4.5 m deep. At 6:30 am, The pipelines in the groove and slope were cleared. At 9:20 am, the 10 m south pit wall between the pile Nos. 20 and 26 collapsed with a collapsed volume of about 10 m^3.	2 deaths
7	Object strike at Section 10 of Beijing metro line #10	Object strike	Beijing	2/27/2006	The rope of mounted hoist crane was broken suddenly during operation. The drop bucket fell down, smashing 3 workers to death.	3 deaths and 1 injury
8	Object strike at Shunyi station of Beijing metro line #15	Object strike	Beijing	7/14/2010	At 4:30 pm, the steel frame for the wall of deep foundation pit in Shunyi station dropped off, smashing 10 workers.	2 deaths
9	Steel collapse at Chongwenmen station of Beijing metro line #5	Object strike	Beijing	10/8/2003	Groups of workers were assembling reinforcement steel bars. The designed spacing of the main steel bars was only 10 cm and the longitudinal spacing of the scaffold bar was 2 m. It was difficult to assemble reinforcement with bars blocking the stirrup. Workers removed one scaffold bar after asking for instructions from vice-monitor and continued to assemble steel bars at 7:50 pm, when workers were trying to pull the stirrup, the scaffold with reinforcement overturned in the entrance direction of pilot tunnel, pinning 4 workers to the ground.	3 deaths, 1 injury and the direct economic loss was 297,000 Chinese yuan
10	Object strike at Xianghu station of Hangzhou metro line #1	Object strike	Hangzhou, Zhejiang Province	11/25/2010	At 12:30 pm, the landslide in the foundation pit smashed 2 drivers in excavators.	1 death and 1 injury
11	Manual excavation of piles for section 3101 at Shaibu station of Shenzhen metro line #3	Toxic gas poisoning	Shenzhen, Guangdong Province	7/6/2009	At 9:25 am, a worker went down to the well and prepared to cast concrete. Five minutes later, another worker found it was unable to contact the first one and decided to check the condition in the well. Both workers lost	2 deaths and 8 injuries

(continued on next page)

Table 1 (*continued*)

No.	Accident	Type	Location	Date (MM/DD/YY)	Process	Consequence
					contact in the well. The supervisor reported immediately to the project manager. At 9:40 am, the 2 workers were rescued from the well, but died 5 min later.	
12	Collapse at section 3106 of Shenzhen rail transit line #3	Formwork collapse	Shenzhen, Guangdong Province	4/1/2008	Concrete casting was started at 10:50 am. At about 1:00 pm, the workers found that the casting process was too fast and requested to stop casting. The casting was suspended for several times. The construction continued after inspection by workers. At 3:10 pm, the casting was paused again for assembling embedded steel bars at the pier top. Workers from concrete casting were going to take a break. When they were climbing down, the formwork and scaffold overturned suddenly to the southeast. Three workers fell down and died, and 2 workers were injured by the falling formwork.	3 deaths and 2 injuries
13	Gas explosion at the Dongjiashan tunnel of Dujiangyan-Wenchuan highway in Sichuan	Gas explosion	Wenchuan, Sichuan Province	12/22/2005	Tremendous gas explosion took place at the Dongjiashan tunnel of Dujiangyan-Wenchuan highway in Sichuan Province.	44 deaths, 11 injuries and the direct economic loss was 20.35 million Chinese yuan
14	Collapse at the Baiyun tunnel of Nanning-Guangzhou high-speed railway	Geological disasters caused by water gushing and mud inrush	Yun'an County, Guangdong Province	1/18/2010	At 8:00 am, water gushing and mud inrush occurred in the Baiyun tunnel. Collapse occurred at the upper left part of the tunnel. The fault has a height of 80 m, length of 16 m and width of 13 m. Mudflow lasted for 30 s and 2500 m^3 mud rushed out by 167 m.	5 deaths and 4 injuries
15	Collapse at the Gaoyangzhai tunnel of Yichang-Wangzhou railway	Rockfall	Enshi, Hubei Province	11/20/2007	At 8:40 am, rockfall occurred at the Gaoyangzhai tunnel, causing a total landslide volume of 3000 m^3. One of the 4 workers was dead, 1 was injured and 2 were missing. Afterwards, 1 bus from Shanghai to Lichuan was reported missing at the accident site.	35 deaths and 1 injury
16	Accident at the Daguishan tunnel of Luoyang-Zhanjiang railway	Explosion	Guangxi Zhuang Autonomous Region	12/10/2006	The 140 kg explosives were left in the tunnel during the day. The night shift workers carried out welding for the shotcrete-blot support.	6 deaths and 1 injury
17	Tunnel collapse at the Xinqixiaying tunnel of Ulanqab-Baotou railway	Collapse	Inner Mongolia Autonomous Region	3/19/2010	At 2:30 pm, the Xinqixiaying tunnel collapsed, killing 10 people.	10 death
18	Water inrush at the Maluqing tunnel of Yichang-Wangzhou railway	Water inrush	Enshi, Hubei Province	4/11/2008	At 5:10 pm, a construction machine collapsed suddenly at the entrance of Maluqing tunnel. When 5 workers entered the tunnel for repairing the machine, water inrush occurred and hundreds of thousands cubic meter water flew into the tunnel.	4 deaths and 1 missing
19	Water and mud inrush at the Yeshanguan tunnel of Yichang-Wangzhou railway	Water and mud inrush	Enshi, Hubei Province	8/5/2007	At 1:00 am, water and mud inrush occurred at the right bottom of the excavation face. The 150,000 m^3 water and 54,000 m^3 mud rushed into the tunnel. Within 220 m away from the excavation face, the tunnel was filled with mud and rock. The mud in other places was 1–4 m thick. The tunnel passed through the Shimaba anticline and the Erxihe syncline. Five underground rivers and channel flow were identified. After the water inrush, a total of 52 workers at 5 tunnel faces were trapped.	3 deaths and 7 missing
20	Water and mud inrush at the Maluqing tunnel of Yichang-Wangzhou railway	Water and mud inrush	Enshi, Hubei Province	1/21/2006	Water and mud inrush occurred at the exit section of the Maluqing tunnel, with a total water volume of 180,000 m^3. Water inrush occurred again for several times during rescue. Dolines, sinkholes and underground rivers were common in the tunnel area. Karst was well developed and the karst water system was complex.	10 deaths and 1 missing
21	Explosion at the Guantoulin tunnel of Wenzhou-Fuzhou railway	Explosion	Lianjiang County, Fujian Province	2/28/2006	At a distance of 50 m from the tunnel entrance, when workers were supporting the formwork of short wall and some were inserting the steel bars while drilling, explosion suddenly occurred in the	3 deaths and 1 injury

Table 1 (*continued*)

No.	Accident	Type	Location	Date (MM/DD/YY)	Process	Consequence
					borehole. Three workers died and one was injured seriously.	
22	Collapse at the Binyang tunnel	Collapse	Guangxi Zhuang Autonomous Region	7/11/2010	Vertical joints existed in the surrounding rock masses, which are likely to cause collapses. The rock was weakened in the presence of abundant water in the mountain, causing collapses.	10 deaths
23	Rockburst at the drainage tunnel of Jinping II hydropower station	Rockburst	Liangshan Yi Autonomous Region, Sichuan Province	11/28/2009	At 0:43 am, extremely strong rockburst occurred when TBM excavated at a depth of about 2500 m. The rockburst produced large amounts of dust, which are scattered in the air for 10 min. The huge energy released by rockburst destroyed the support system, causing collapse in large areas in the roof and two sidewalls. About 1000 m^3 rock ballast buried the main engine of the TBM and broke the main girder. Eight workers were buried, with 7 dead and 1 injured.	7 deaths and 1 injury
24	Tunnel collapse at Diqing Tibetan Autonomous Region	Collapse	Shangri-La County, Yunnan Province	3/29/2011	At 4:00 pm, due to the unstable geological strata, the Kengu tunnel, which had been supported, collapsed suddenly. Nineteen workers were trapped in the tunnel.	19 injuries
25	Water and mud inrush at the Taoshuping tunnel of Lanzhou-Chongqing railway	Water and mud inrush	Yuzhong County, Gansu Province	11/4/2014	At 3:10 pm, water and mud inrush occurred at the Taoshuping tunnel of Lanzhou-Chongqing railway. Nine workers were buried and 1 was dead.	1 death and 9 injuries
26	Collapse of the road drainage at the east stretch of Songshan Road	Collapse	Suyu, Jiangsu Province	4/4/2012	At 8:50 am, collapse occurred when 5 workers were constructing the pipeline foundation at the trench bottom. Five workers were buried.	3 deaths and 1 injury
27	Collapse at Xi'an metro line #3	Collapse	Xi'an, Shaanxi Province	5/6/2013	In the early morning, the tunnel section between the Tonghuamen station and the Hujiamiao station of Xi'an metro line #3 was excavated to a depth of 8 m. Tunnel roof collapsed suddenly when 9 workers were working.	5 deaths

The accidents with precursors before failure account for 75% among the total accidents (Fig. 9). The main reason for some accidents with precursors in tunnels is that the precursors are not identified by the superintendent or no countermeasure is taken by the contractor. For instance, before the "12.22" major gas explosion accident in the Dongjiashan tunnel of Dujiangyan-Wenchuan highway in Sichuan (case 13 in Table 1), the tunnel face collapse and abnormal gas gushing led to extremely high gas content near the platform. The short circuit of three-pin plug near the distribution box of the formwork trolley initiated sparks and caused gas explosion. As the superintendent did not perform the duties properly and non-qualified staff was appointed on the key post, the precursors were not identified. In many cases, no proper countermeasures were taken by the contractor, and little attention was paid by the superintendent and contractor to the precursors. For instance, the surface collapse took place in the Xianghu station of Hangzhou metro line #1 (case 4 in Table 1). A non-qualified chief engineer was appointed for quality control and documentation. During excavation of N2 foundation pit, the cracks on the roads and the displacements in the sidewall of foundation pit were observed. Four alarms were raised by the monitoring data. However, no effective measures were taken and eventually the accident occurred.

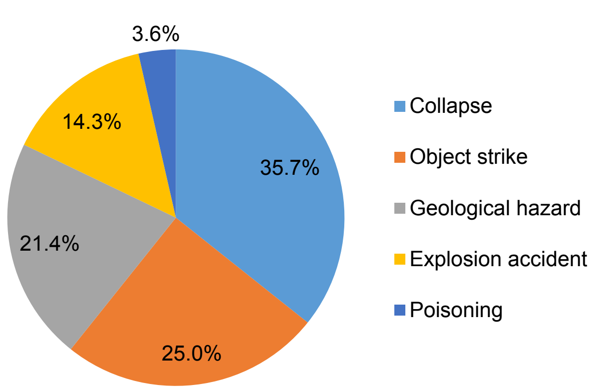

Fig. 8. Classification of major accidents during underground construction in China.

(2) Problems associated with the contractor

Firstly, poor safety awareness and unreasonable construction scheme due to deficiency in the existing construction techniques are the main causes (Fig. 10). For example, during construction of Yichang-Wanzhou railway (case 15 in Table 1), geological hazards, such as water and mud inrush, were frequently reported. On 21 January 2006, unprecedented catastrophic flood occurred in the Malujing tunnel. After successful rescue, a tunnel was built for flood discharge in order to eliminate the risks during the construction and operation periods. The flood discharge tunnel project started in August 2006. On 11 April 2008, three days after successful flood discharge, water inrush occurred again, leading to 4 deaths and 1 missing. Violation of operation rules, improper instruction, lack of safety training for workers, and lack of safety technique disclosure were the most important reasons of the accidents, for instance, the

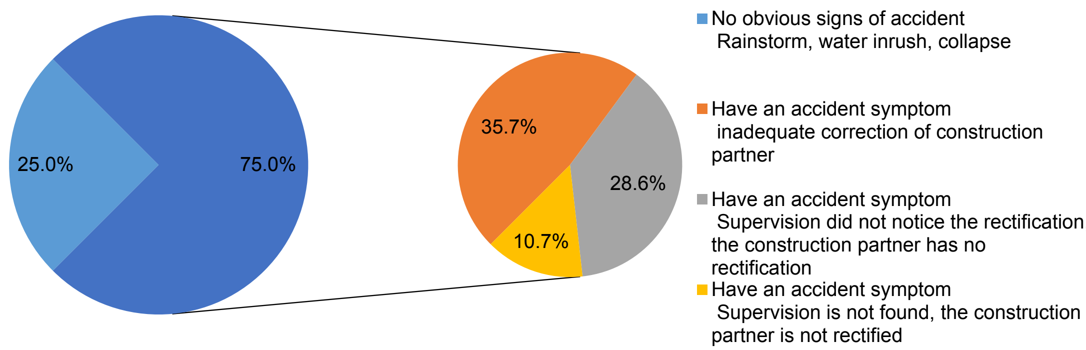

Fig. 9. Proportion of various accident precursors.

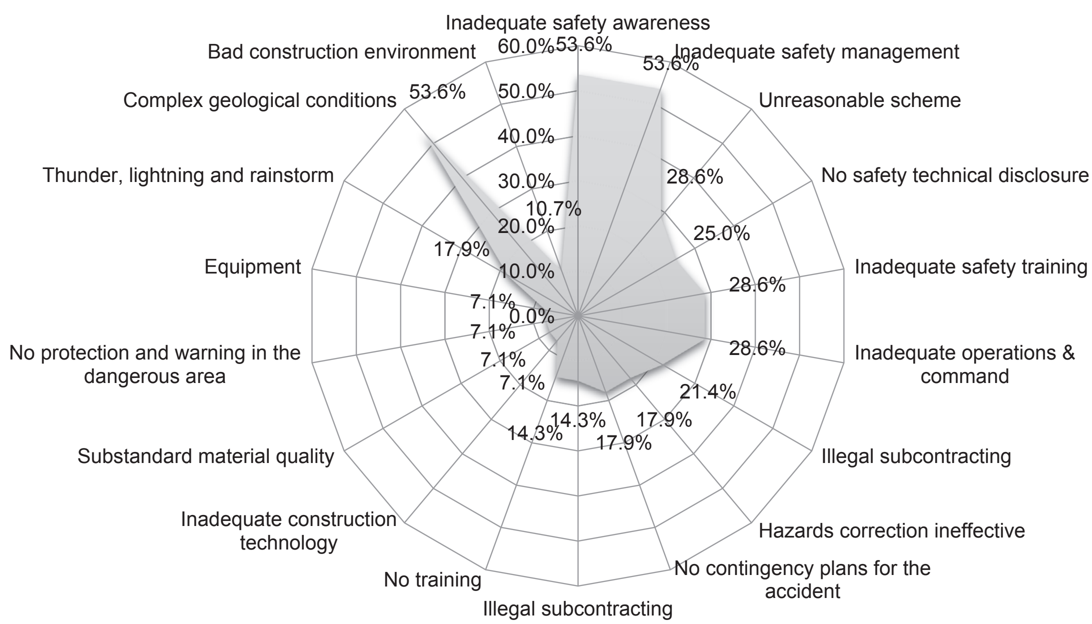

Fig. 10. Accidents due to problems associated with contractor.

object strike accident in Beijing metro line #10 (case 7 in Table 1). In this case, the crane was not checked carefully before the relevant staff signed the acceptance report, and the site manager was lack of law awareness and signed the acceptance report before checking the crane. No measures were taken timely and construction was carried out as schemed. Secondly, illegal subcontracting, improper rectification of hidden dangers, and unqualified appointment are also the common reasons. In addition, improper construction techniques, poor material quality, improper operation of equipment, and no warning signs at the dangerous zones are also the common reasons for accidents.

(3) Problems related to the superintendent

Nonfeasance and poor supervision ability exist in the tunnel projects. Different from other projects, a higher portion of accidents were caused by poor identification of hidden dangers and lack of professional supervision knowledge, indicating the lack of professions in superintendent for underground projects. In addition, low responsibilities are taken by the superintendent, such as violations of inspection and acceptance rules and no countermeasure taken after identifying hidden troubles. In the surface collapse of the Xianghu station of Hangzhou metro line #1 (case 4 in Table 1), the superintendents did not perform their duties, for instance, approval of the report for a dangerous construction scheme without careful examination, forceless determent on violations of rules and regulations by the contractor, and delay in reporting to the developer and relevant quality supervision departments. The superintendent did not carry out inspection and acceptance for the project according to stipulations.

(4) Problems related to survey and design

As the tunnel projects are constructed underground, survey data are very important for construction safety. For instance, the "3.19" major collapse in the Xinqixiaying tunnel of Ulanqab-Baotou railway (case 17 in Table 1) was one of these accidents. At 2:30 pm, the Xinqixiaying tunnel collapsed and killed 10 people. The rock masses along the tunnel alignment are of poor quality and self-stability. The tunnel collapse was caused by insufficient survey depth, untimely and inactive tracking and monitoring of the changes in the surrounding rock masses after excavation, and early commencement of design and construction without inspection and acceptance of geological survey data. Sometimes, accurate survey data cannot be obtained due to complicated geological conditions.

(5) Problems associated with the project owner

One of the problems associated with the project owner is the poor supervision, such as the surface collapse accident in the Xianghu station of Hangzhou metro line #1 (case 4 in Table 1). The owner did not supervise and manage severe hidden dangers properly during the construction process, which was a serious breach of duty. The other is caused by illegal contracting, such as the "3.19" major collapse in the Xinqixiaying tunnel of Ulanqab-Baotou railway (case 17 in Table 1). The standard tendering procedures were not followed by the Mengji Company. The project owner did not supervise the construction strictly. For example, no experts were organized and invited for inspection and acceptance of the survey data in the stipulated time, and the project was started without approval.

3.3. Combined causes of accidents

(1) Individual and departmental interests

The individual and departmental parts mainly refer to some important figures in related units. A few important persons only consider their own achievement and interests, and various important factors are neglected, such as the project scale, construction period and cost of scientific research. The construction process and detailed bidding are frequently and randomly interfered due to their "power" on project management. Underground projects are becoming the corruption disaster center by power rent-seeking. The owner usually has a tendency to have bidding at a low price, and randomly delays the payment for construction contractor, and shortens the construction period which is out of the schedule. Under the low bid price, the construction contractor has to reduce the cost on safety, design and construction at the same time due to profit margin. Worse, the construction contractor will employ unlicensed workers, regardless of the national and/or industry standards.

(2) Safety inspection just becoming a mere formality

The concept of "massive safety inspection" originates from the political thinking that only focuses on the important person's opinion. The formalism of safety management includes law system and regulations not being efficiently implemented at construction site, which in turn testifies that no one will follow the rules. The government representatives pay attention to the format of examination rather than true inspection, and once an accident occurs, the government representatives only rely on "massive" one-time safety inspection, not on on-site check of the safety management of the enterprises. In this regard, the associated enterprises will be shut down due to the pressures imposed by the superiors and public opinion. Therefore, a scientific engineering safety risk system needs to be established, and the implementation and supervision must be strictly and carefully controlled, while the political thinking and leadership culture in terms of lack in responsibility should be discarded.

(3) Malfunction of governmental supervision

The governmental supervision is usually characterized with multiple and cross leaderships, which is highly dependent on merely using examination and approval mode. This is usually conducted with little attention paid to effective supervision, leading to the lack of independence of inspection. In addition, the government-based investment project implements the notion of "who invests, who manages". At present, the government-based investment project shares the largest percentage in underground construction projects in China. In those projects, the government has a double identity in terms of the supervision and owner. For example, a vice mayor of a city is usually in charge of important urban infrastructure projects. In this circumstance, the multiple and cross leaderships can cause the safety inspection being lack of independence, in the absence of the support of professional institutions and experts team for safety risk management. For an illegal contract and multi-level contract, the government supervision organization has limit capacity to inspect all government-based projects due to the enormous projects under quality control, leading to the occurrence of accidents.

(4) Safe management responsibility

The safe management responsibility is basically not clear, reasonable, and mature, thus the safety management cannot cover the whole process of construction. According to the related regulations and rules in China, the construction safety responsibility is almost entirely implemented by the construction enterprises, and the safety management is only focused on construction stage. The owner is the major role that affects safety control, which is responsible for the schedule and construction cost.

(5) Inadequate employment system

The employment system is also not reasonable, in which the untrained workers are vastly employed. Concerning the current labor system in China, a majority of on-site construction employers are migrant workers in order to reduce the construction cost in terms of the migrant employment. This is a common issue. Currently, the population movement of rural migrant in China is significantly large; however, they are basically of poor education. Due to the lack of professional training, the safety consciousness of migrant employment is generally very low. In this regard, they will do at will during construction, not following the construction scheme. Thus brutal construction and operation are a serious problem in field construction.

(6) Unchecked engineering geological data

Engineering geological survey data are basically not examined or checked by the third independent institution. In addition, the construction plan review is missing or inadequate. Based on accident case analyses, the incidents induced by inadequate geological survey data, design and construction plan rank top 2, which account for 83%.

(7) Ambiguous experts' system

The experts' system in engineering evaluation, design and construction plan has the potential defects. Basically, the defects are shown in a form of short-time evaluation, and no detailed and complete review is used for design and construction plan. Experts are usually invited by the owner; therefore the opinions from experts that are not in favor of the owner's intentions would not be adopted. The true suggestions from the experts will not appear in any risk or safety evaluation. Moreover, there is no recourse responsibility mechanism for the experts who propose a false evaluation.

In view of the current major problems, the laws and regulations are not perfect (or mature) for the construction safety management. Although the government has set up the legal framework for the normal development of construction market (Fig. 2), and the associated regulations and standards for the safety management, the operability in underground construction safety management is weak and, the mandatory regulations considering China's facts do not adopt foreign advanced experiences. The main problems of safety management include the government intervention, lack of responsibility of the owner, artificial construction duration compression, low cost, low investment on safety management, and low number of qualified staff in project site.

4. New challenges in safety risk management

From Sections 2 and 3, although great progress has been made in safety risk control for underground engineering in China, there are still many challenges, particularly safety behaviors of personnel, technological innovation of safety risk management, and design of regulations and rules for underground construction.

4.1. Challenge 1: safety behaviors of personnel

In 2014, the scale of migrant workers reached 274 million in China, among which the migrant workers in construction industry were 61.09 million, accounting for 22.3% (National Bureau of Statistics of China, 2014). The migrant workers in the construction industry generally have low education level, poor safety awareness and knowledge. Frequent accidents have called for higher requirements for safety management. Heinrich et al. (1950) proposed the pyramid theory, which stated that, in a workplace, for every accident that causes a major injury, there are 29 accidents that cause minor injuries and 300 accidents that cause no injuries. Therefore, accidents in underground construction can be effectively prevented by controlling the unsafe behaviors of workers and management staff.

The research group led by Professor Ding carried out studies on recognition, laws and rectification methods for unsafe behaviors during subway construction, based on the visual language (Fig. 11) (Ding and Zhou, 2013; Ding, 2015; Ding and Guo, 2015; Guo et al., 2015). Since 2009, more than 80,000 photos have been collected on the unsafe behaviors of construction workers. First, the vector space model (VSM) (Ding and Guo, 2015; Guo et al., 2015) and the sentence similarity algorithm based on multi-level information fusion are adopted to analyze the unsafe behaviors in the photos and the semantic information is extracted.

By using the behavior dynamics method, the distribution of time interval between unsafe behaviors is investigated. The results (Ding and Zhou, 2013; Ding, 2015) show that:

(1) The time interval of unsafe behaviors during underground construction is heavy-tailed, i.e. the unsafe behaviors of workers are paroxysmal. One type of unsafe behaviors may not take place in a long period, but may occur frequently in other duration.
(2) The unsafe behaviors of machine operators fluctuate frequently. During excavation, the frequency of such unsafe behavior that "unauthorized workers move around the excavator under operation" reaches 9.6%.
(3) After being rectified by the system, the rate of unsafe behaviors is reduced by nearly 60%.

With the rapid development of metro lines in China, the daily passenger flow in some cities has reached more than 10 million per day. Large passenger flow in the metro station means a high risk. In view of these problems, Zhong et al. (2003, 2006) proposed a theoretical calculation model with assessment indexes for the maximum passenger capacity of different subway platforms. The individual-based simulation technique for large subway passenger flow is established. The formation and diversion mechanism of large passenger flow is revealed. A complete set of safety analysis models for subway passenger transportation (Fig. 12) is proposed. The monitoring and early-warning system for subway passenger flow is developed to realize real-time warning of unexpected large passenger flow (Zhong et al., 2003, 2006). The calculation model for subway evacuation is put forward, which has been adopted in the design of evacuation passage at subway stations in more than 10 cities, including Beijing, Guangzhou, Shenzhen and so on. With the above theories and techniques, the safety issues in case of large passenger flow are solved successfully in the Dongdan station and Zhichun road station of Beijing metro, and the Huangcun station of Guangzhou metro.

4.2. Challenge 2: technological innovation of safety management

Based on statistics of 550,000 accidents, Heinrich et al. (1950) proposed the pyramid theory in 1941: the ratio between death or major injury, minor injury, non-injury and hidden dangers is 1:29:300:1000 among all the accidents. For different production processes or different types of accidents, the above relationship may not be always applicable. However, the statistical law and the theoretical model indicate that, in any project, numerous accidents will inevitably lead to significant casualties. In order to prevent major accidents, attention must be paid to signs or precursors of accidents, and non-injury accidents shall be reduced or eliminated. Otherwise, major accidents will eventually occur.

Due to the impact of external forces (artificial or natural) or intrinsic and extrinsic factors, the balance is broken or some abnormal phenomena or precursors occur before an accident. This imbalance generally implies a process from quantitative change to qualitative change, which usually lasts for a certain

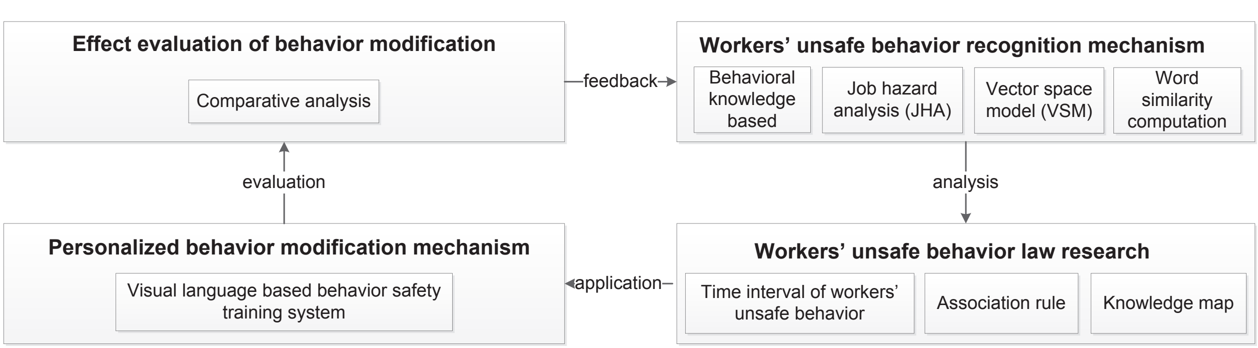

Fig. 11. Flowchart for analysis and extraction of unsafe behaviors of the workers (Ding and Guo, 2015; Guo et al., 2015).

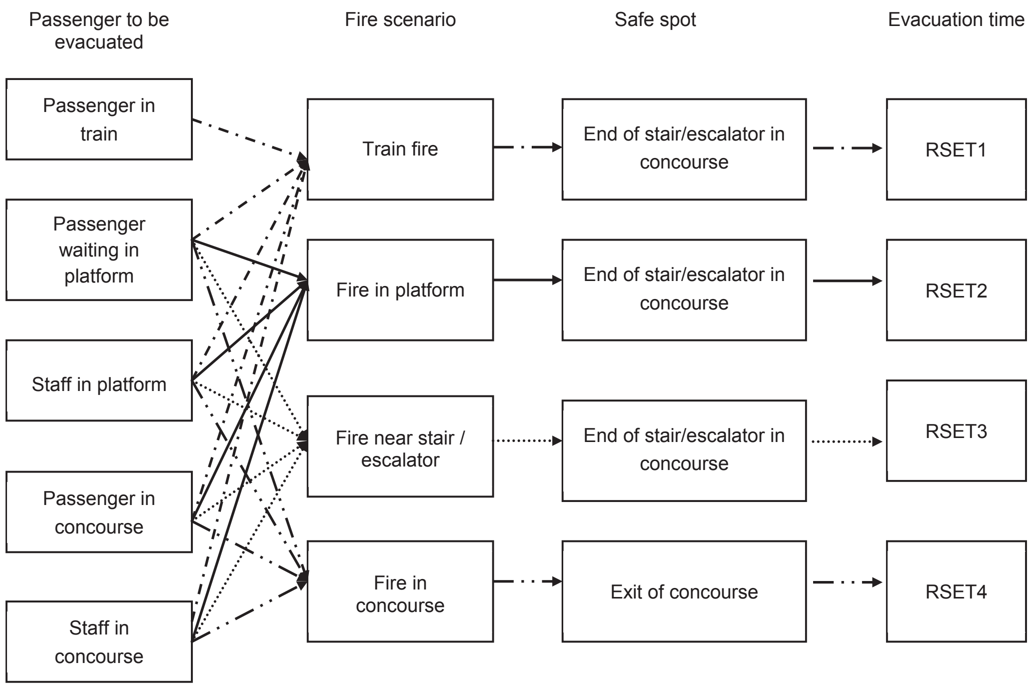

Fig. 12. Passenger evacuation strategy of metro station (Zhong et al., 2008). RSET means the required safety egress/escape time.

period of time. According to the statistics on relevant cases, a large number of precursors exist two or three days to one week before the accident occurrence. However, due to insufficient attention or mishandling of the precursors, the accident finally occurs (Fig. 13). The precursors of accidents or disasters must be studied to identify some abnormal phenomena when the balance of an object is broken. Accordingly, people shall take certain precautions to avoid injury or property loss. Thus, in combination

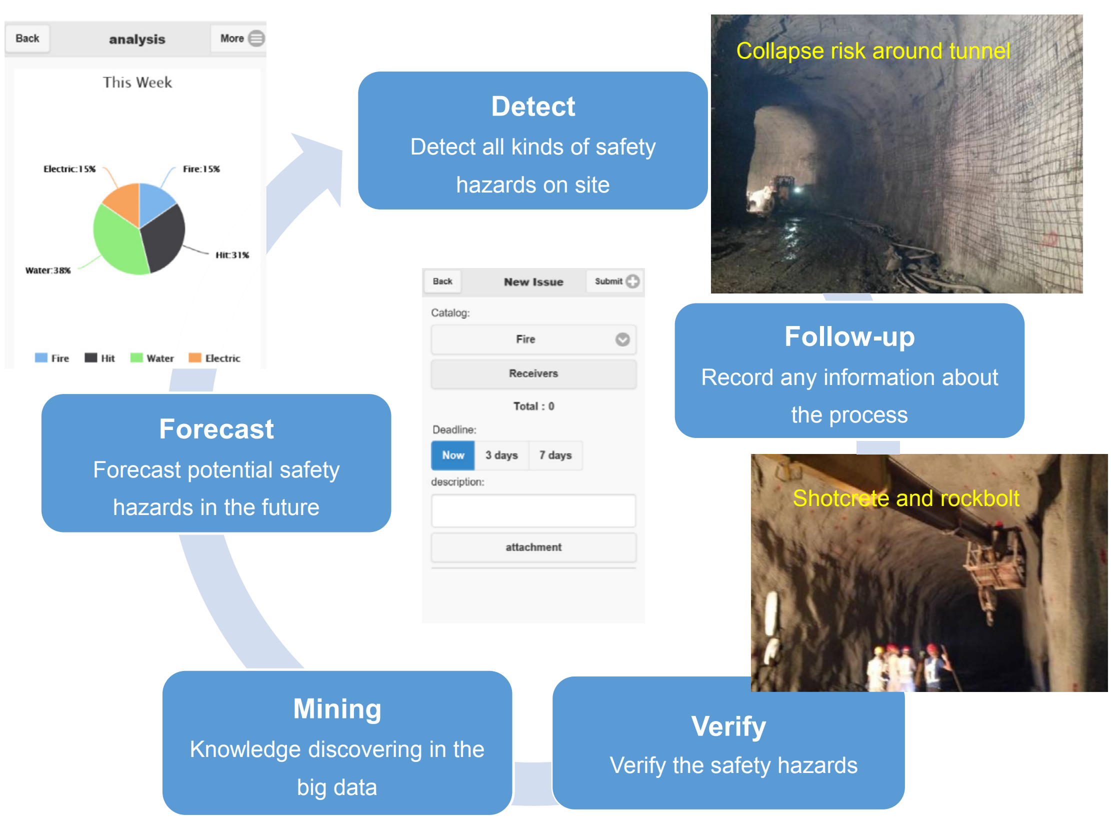

Fig. 13. Safety risk management system based on WeChat.

with the characteristics of underground construction, timely capture of anomalies or irregularities by instruments, experiences and observations, and proper countermeasures can help to eliminate the accident or disaster before it occurs, so as to minimize any losses. Studying the phenomena and applications accident precursors is the most effective way to prevent and reduce accidents or disasters.

(1) Integrated safety management and control of metro construction based on building information modeling

The building information modeling (BIM) is able to integrate safety management, utilize safety information sources and avoid loss of safety information. Lifecycle safety risk management for metro projects can be achieved by using the BIM method. Safety management covers the entire process of metro construction:

(i) The concept of forward shifting of safety management shall be followed. At the design stage, structural safety analysis and optimization of design schemes shall be performed. Collision detection shall be simulated to identify conflicts between components or equipment in advance so as to avoid safety risks.
(ii) During construction, a digitized construction site can be built based on BIM. The real-time safety status can be perceived through the internet of things. The digital site and physical construction site are interconnected so that the digital site serves and guides the physical construction site and dynamic isolation of safety risk energy can be achieved. The results have been applied successfully to construction of the river-cross tunnel (Ding et al., 2014) and station (Chen and Luo, 2014).
(iii) In the operation stage, the maintenance plans for equipment and facilities are generated and the evacuation plan in case of emergency is simulated by using the BIM. The BIM technology is also applied to integrating the management tasks of the metro project, so as to achieve synergy of safety, quality, progress, cost and other operations. The responsibility can be traced back to ensure the project quality and effectively reduce the potential safety risks (Ding et al., 2014).

(2) Real-time online safety risk management based on WeChat

In general, the large-scale underground projects are always located in a complex terrain environment. Due to high construction speed, long construction period, and complex interactions between dynamic and complex hidden dangers among workers, machines and environment, the safety risk management is quite difficult. In 2011, Tencent Inc. launched a new instant messaging platform based on mobile internet, WeChat, which has been commonly recognized and widely used nowadays. Lin et al. (2015b) established a real-time online reporting system for potential safety risks of workers by the following steps (Fig. 13): (i) reporting of safety risks; (ii) analysis of reported data; (iii) distribution of hazard information; (iv) rectification of hidden hazard; (v) analysis of data after rectification; and (vi) closing of hidden hazard. The system includes interactive interfaces and back-end cloud server. The cloud server consists of (i) a data acquisition module, which sends the hazard report by WeChat, (ii) a data identifying module, which analyzes the reported data, identifies the data type and source, and sends the data to the processing center, (iii) a cloud messaging module, which sends information in categories and provides personalized service, and (iv) a data analysis module I, which performs correlation analysis and condition query among the data, spatial location information and attribute data based on the spatial location information. With this system, information of various safety hazards encountered at large-scale construction sites can be collected and reported to the back-end cloud system by the mobile tool WeChat. By data analysis and data mining, enhanced management, personnel and property safety, effective monitoring of the project quality can be achieved eventually. Currently, the system is successfully adopted by Baihetan and Xiluodu construction sites.

4.3. Challenge 3: design of safety management regulations

Heinrich (1941) investigated 75,000 industrial injuries in USA and found that 98% of accidents were preventable, and only 2% of accidents beyond human ability were not preventable. Table 1 shows that most accidents are preventable in the underground construction field. Statistical analysis also shows that precursors occurred two days to one week before the accident (Fig. 10). If attention had been paid to these precursors and proper measures had been taken in time, accidents could have been completely avoided.

The safety science and engineering theory supports the standpoint that the accidents can be prevented, which provides the following methods and principles for accident prevention:

(1) The energy release theory indicates that the accident risk sources can be divided into two categories: static and dynamic risk sources. With protection technology and treatment (such as increasing the design safety factor), the triggering threshold of static risk sources can be enhanced, and the possibility of risk source outbreak and the hazard level after the accident can be reduced. By daily safety risk management, unsafe behaviors of workers and unsafe state of materials can be eliminated. Hence, the accidents triggered by dynamic risk sources can be controlled.
(2) The Heinrich's pyramid theory and the causal chain accident theory indicate that as long as the daily unsafe behaviors of people and unsafe state of materials are eliminated, less unsafe factors are accumulated and the direct causes of accidents are cut off. As a result, accidents can be avoided.
(3) The Surry model provides a good idea for accident prevention. In order to prevent and control the accidents, technical means should be firstly employed to reveal the dangerous state (precursor), so that the operator can have better awareness on the presence or release of hazards. Secondly, training and education shall be conducted to improve the sensitivity of workers on danger signals, including anti-interference ability and so on. Thirdly, by means of education and training, the operator can accurately understand the meaning of the warning signal, and know what measures should be taken to avoid the accident or to control its consequences. Proper decision can then be made. Finally, the system and its ancillary facilities should be designed in such a way that people have sufficient time and condition for response after proper decision is made. In this manner, the accidents can be controlled to a great extent and good preventive effect can be achieved.

5. New strategies of safety risk management

5.1. Objects of safety risk management for underground engineering

In the background that China is comprehensively deepening the reform and promoting the spirit of administrating the country by law, the relevant laws and regulations are being reformed and enhanced. Correspondingly, actions are taken to achieve the following goals for the safety risk management of underground engineering. The policies and systems of safety risk management for underground engineering should be established and promoted in China. The system and mechanism of safety supervision should be reformed. The manner of supervision should be improved and the supervisory force should be strengthened. The major role of the project owner in safety risk management should be implemented. The market economic means should be introduced to ensure the guarantee policy. The employment policies should be reformed to establish a qualification licensing system. The long-term and effective mechanism of safe production in the construction industry shall be promoted. By 2020, the state of safe production in underground engineering in China shall be significantly enhanced, and the major accidents shall be effectively controlled. By 2030, the state of safety management in underground engineering should be substantially improved.

5.2. Strategies

Valuable lessons have been obtained from bloody accidents in the construction projects, which reveal that safety risk management must be transformed from passive remediation to proactive planning and prevention. This relies on the combination of technological, managerial, cultural and legal approaches to establish a comprehensive safety risk management system. According to the discussions on progress and challenges in the earlier sections, the safety risk management mode of underground engineering in China is still at a preliminary level or a low level in some regions. The major task of policy makers and researchers is to actively guide the safety risk management mode of underground engineering towards the intermediate level of systematic and scientific safety risk management, and gradually transform toward a high level with safety culture. In this paper, it is suggested to address the problem based on strategies from six perspectives, including management system and policy, law, administration, economy, education and technology, as shown in Fig. 14.

Fig. 14 shows that the theoretical basis of the new strategies is the “3E” theory, i.e. enforcement, education and engineering. The detailed implementation methods include the legal, administrative, economical, educational and technological methods.

The strategy of management system and policy is to establish and promote the safety risk management system and policy for underground engineering which are in line with the international conventions. The safety risk management should be transformed from “rectification after accidents” to “prevention in advance”. Meanwhile, the safety risk management mode should be improved from being oriented by experiences and policies to the systematic and scientific stage, and gradually transformed to the stage with safety culture. The safety risk management should be tightly combined with project management and be treated as a mandatory procedure and a core content of project management. Hence, the following four aspects have to be implemented. Firstly, the safety risk management has to be regulated by relevant laws. Particularly, a series of laws and regulations need to be legislated, issued and implemented. For example, “Regulations on safety risk management of underground construction” can be implemented to enforce the mechanism of risk management and guarantee system. Secondly, an integrated modern safety risk management system, characterized by lifecycle management, various risk-related factors, complete management process and implementation of risk responsibility, should be established. The objective, scientific and dynamic system can be used to identify accident precursors in order to control risks and reduce the uncertainties of accidents. Thirdly, the organization management system, technology management system, risk monitoring, emergency management system and safety culture system should be established comprehensively. The safety risk management system should be all-around during the entire construction process. All-around management refers to the involvement of government and market, including the government department, the owner, the contractor, the engineering guarantee and insurance company and the consultant. The whole-process management refers to management in various construction stages, including planning, design and construction. Risk identification, analysis, assessment, monitoring and early-warning should be performed throughout the entire process. Finally, modern technologies should be introduced into the safety risk management system to strengthen the real-time monitoring of safety risks and project quality, and to enhance the capability in identification and treatment of accident precursors.

The legal strategy aims to provide a strong basis for regulating the safety risk management. Through legislative and contractual methods, the construction industry should promote establishing an engineering guarantee system. On the basis of “Guarantee law”, “Contract law”, “Construction law”, “Bidding law” and “Regulations on quality management of construction engineering”, national and regional legislation should be specified in engineering guarantee and insurance. Related laws and regulations should prohibit any bidding with unreasonable low price. The most urgent task is to establish and promote “Regulations on safety risk management of underground construction” in all engineering companies and projects. “Regulations on safety risk pre-evaluation management of underground construction” has defined the supervisory

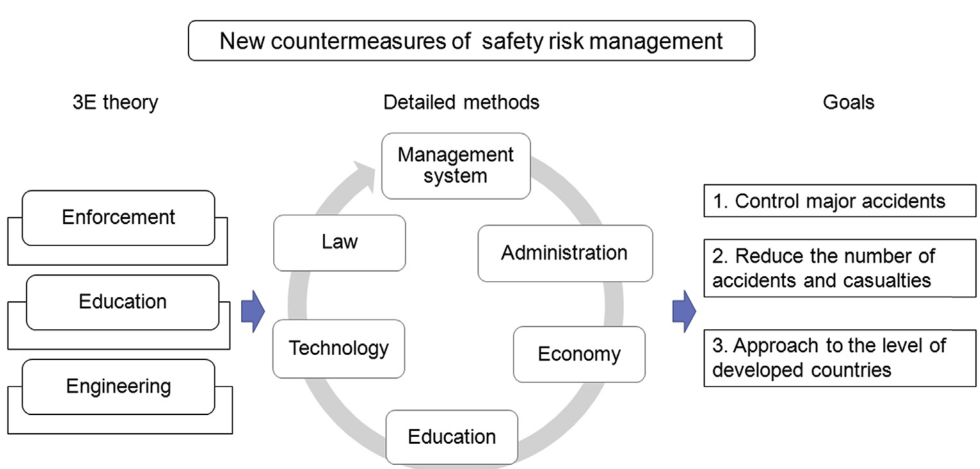

Fig. 14. The goal and new countermeasures of safety risk management of underground engineering in China.

responsibilities of the government and the respective responsibilities of the project owner, design institute, contractor, and companies involved in survey, monitoring and superintendent in the construction process. The so-called "tribute project", "image project" and "special case" should be strictly prohibited. "Regulations on comprehensive supervision of safe production of underground projects" should regulate the approval process of safety risk management for major engineering projects. The project with extremely high risks should be vetoed by experts. "Regulations on review of investigation, design, and construction scheme of underground projects" specifies that geological investigation results, design schemes, construction schemes and the corresponding drawings should be reviewed by the qualified third party. "Regulations on guarantee and insurance of underground projects" and "Regulations on qualification licensing of superintendent, design engineer and construction engineer for underground projects" are mandatory to ensure that the safety risk management system and engineering guarantee and insurance system can be implemented in underground construction.

For large-scale tunnel or underground projects, the chief supervisor should be a registered geotechnical engineer. In addition, training of practitioners should be strengthened. Particularly, the responsibility of government departments and enterprises in labor training, especially for the migrant workers, should be specified. In order to ensure the safety of products and devices, the third-party authentication policy should be established. When establishing the relevant laws and regulations, punitive measures should be adjusted according to regional economic development levels in China. Stiff punishment should be imposed on illegal activities that may induce serious damage to public, environmental, personal and property safety. Higher cost of illegal activities can help to regulate the behaviors of all parties involved and subsequently reduce safety accidents. Meanwhile, guiding books and manuals shall be published for better understanding of the laws, regulations, guidelines and technical standards.

The administrative strategy aims to build a harmonious environment for the construction industry by mobilizing the system and mechanism of market economy. The roles of government, enterprises, supervisor, guarantee and insurance companies and consultants should be explicated. Detailed suggestions include the following seven aspects. First, the industrial structure of construction should be reformed. Leading enterprises are at the upstream of the industry, in charge of contracts of national major projects. The mainstay of the industry is supported by subsidiary companies of the leading enterprises or medium-scale contractors, in charge of general civil construction projects. The downstream of the industry is composed of small and flexible labor service companies, undertaking labor subcontracting. With this kind of industrial structure, companies in different levels have a stable number of employees for the purpose of safety education and training, which can improve the efficiency of safety risk management and cultivate a safety culture. Second, the construction industry should promote reformation of the migrant labor system and gradually transform the migrant workers into professional workers of labor service companies. Third, reasoning and recording system shall be established for proper project schedule and cost. The associated documents should consider the liability recourse. Fourth, the owner should play a predominant role in safety risk management. The owner should regulate the tendering and bidding process and promote the transparency of the tendering and bidding process. Fifth, in addition to strict control of qualification licensing for companies, the access permission policy for technical personnel should be strengthened, particularly the registered engineer system. The rights and responsibilities of registered engineers in safety risk management should be specified. "One certificate is affiliated with several companies" or "the registered engineer lends his or her certificate to non-qualified companies for bidding" should be prohibited. Sixth, the supervisory management model for safe production should be reformed. The focus should be placed on supervision of establishment and implementation of the engineering guarantee system, the safety risk management system and the safety regulations and standards, rather than on the detailed safety risk management processes of companies in a manner of single-targeted and occasional massive campaigns. Random inspections and surveillances should be carried out, rather than just notifications. The safe production credit system, the reporting and punishment system of major accidents should be established and enhanced. The illegal or improper behaviors of companies should be released to the public on a regular basis, and the public supervisory power should be strengthened. Seventh, the supervisory management system, mechanism and team for safe production in the construction industry should be reformed.

The economic strategy focuses on the following four aspects. First, the engineering guarantee and insurance system should be established and promoted, through legislative and contractual means. Based on "Guarantee law", "Contract law", "Construction law", "Tendering and bidding law" and "Regulations on quality management of construction projects", the content of engineering guarantee and insurance shall be extended to form national laws and local regulations. Second, the guarantor market with proper competition shall be cultivated, and the risk management agency shall be developed as the guarantor. In view of China's facts, intercompany guarantee of the major contractors should be developed with first priority. The third-party guarantee can be provided by contractors with strong ability and good reputation. Third, the risk management consultants can be employed as the brokers and agents for engineering guarantee. The consultants can be commissioned to negotiate with the guarantee company, claim for compensation, develop the risk management techniques, and conduct training and risk consultation. Fourth, the construction industry should rely more on third-party credit investigation companies, establish the databases for recording safety and financial credit of engineering companies, and ensure that the guarantors can obtain the credit information of the guarantee companies. Therefore, different players in the construction market will gradually become more credible.

The educational strategy focuses on the following three aspects. First, the government and the contractors should put more efforts to the training of rural migrant workers. The development and promotion channels for rural migrant workers shall be solved, so as to realize transformation from migrant workers to professional workers. Second, the quality and professionalization of practitioners shall be promoted in the construction industry. Third, more attention shall be paid to safety education of technical professionals in underground engineering, such as continuing education on safety.

The technological strategy includes the following aspects. First, technical standards of investigation, design, construction and acceptance should be enhanced. Higher standards related to safety risk management, including project durability, should be enforced. More resources shall be used in researches of safety risk management and technology. Second, in order to promote the management of technical standards, compilation of technical standards shall be implemented by relevant societies and associations. Meanwhile, the technical standards shall serve as technical guides and more emphases shall be put on recommendation of technical methods, in addition to the key technical parameters involved in the safety and quality bottom lines. Third, the leading companies and local governments shall be encouraged to establish company standards and local standards. The national standards are the basic standards with the lowest requirements. The local standards should conform to the economy and society development levels in the region. The company standards should be the standards with the highest requirements. Fourth, during the planning stage, sufficient time shall be ensured for investigation, reasoning and design. The time for design cannot be artificially cut down and "design while construction" should be prohibited. Fifth, the expert review mechanism for the key technical works should be reformed. The expert review mechanism is suggested to be replaced by the third-party independent review mechanism. Professional and detailed examination of investigation, design and construction schemes should be conducted by the third-party consultants. The consultants should comment on the examination results and are responsible for the comments proposed. Sixth, a safety risk management intelligent and information system should be established.

5.3. Intelligent and information technology

For improving safety risk management of underground engineering, an intelligent system should be developed, which can provide a communication platform for different parties involved in the construction project. Based on the modern intelligent and information technology, monitoring data can be delivered to relevant parties in real time. Activities and behaviors of different parties are transparent in the whole system, which is beneficial to information sharing, mutual supervision and responsibility implementation.

The intelligent underground engineering (IUE) incorporates digital and real underground engineering, which depends on the integration of networking and digital technology. The IUE achieves a unified space-time reference for four-dimensional information show. By employing cloud computing and big data mining method, the IUE can rapidly process and dynamically update the sensor data in real-time, and provide intelligent services based on the perception, logical thinking, self-adaptive and decision-making abilities. The intelligent services include real-time intelligent analysis, data mining, knowledge discovery and real-time decision.

The IUE performance characteristics are described as followings:

(1) Real-time perception: Smart sensors are installed for comprehensive perception and real-time monitoring running state of tunnel, environment, equipment and people.
(2) Comprehensive internet: Using the internet of things, all comprehensive sensors are connected with each other, and intelligent storage and transmission on sensing data are realized.
(3) Deep integration: Combining with the networking and internet of things, integrating multi-source data, which will provide a safety risk management mapping of underground engineering construction and operation.
(4) Intelligent service: Based on the intelligent information infrastructure (network, data), cloud computing, data mining and knowledge discovery, a new system structure can provide intelligent service for the construction and operation periods of the underground engineering.

6. Conclusions

This paper discusses the main progress of the safety risk management of underground engineering in China in the past decade, i.e. (1) establishment of laws and regulations on safety risk management, (2) implementation of the safety risk management plan, (3) risk management and early-warning decision support system for underground engineering based on information technology, and (4) strengthening the studies on safety risk management, prediction and prevention for underground engineering.

In China, the combined cause of safety accidents except for direct causes are summarized as follows: (1) individual and departmental interests, (2) safety inspection merely becoming a mere formality, (3) malfunction of governmental supervision, (4) safe management responsibility, (5) inadequate employment system, (6) unchecked engineering geological data, and (7) ambiguous experts' system.

The safety risk management of underground construction in China involves hundreds of millions of people, large construction sites, and complex construction processes. The new challenges of the safety risk management of underground engineering include (1) control of unsafe behaviors of workers, (2) technological innovation related to safety risk management, and (3) design of safety management regulations. The history of safety risk management in the developed countries shows that with long-term persistence of legal and scientific management, a high level of systematic and scientific safety risk management with safety culture can be achieved.

New strategies of safety risk management for future underground construction in China are proposed in six aspects, including the safety risk management system and policy, legal, administrative, economic, educational and technical countermeasures. Only in this way, a fundamental improvement in the safety risk management in China can be realized.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

This study is supported by Chinese Academy of Engineering (grant No. 2011-ZD-12), National Natural Science Foundation of China (grant No. 11272178) and National Basic Research Program of China (973 Program) (grant No. 2011CB013502/3). The authors are very grateful to Profs. Shigang She, Songqing Lin, Xiaoli Rong for their critical recommendations, which have greatly helped the authors to improve the paper.

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