Journal of Civil Engineering and Management
ISSN 1392-3730 / eISSN 1822-3605
2019 Volume 25 Issue 4: 362–379
https://doi.org/10.3846/jcem.2019.8652

RELIABILITY MODEL AND CRITICAL FACTORS IDENTIFICATION OF CONSTRUCTION SAFETY MANAGEMENT BASED ON SYSTEM THINKING

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Received 09 July 2018; accepted 14 January 2019

Abstract. Safety is a key objective of construction management, but construction safety management is complex due to various types of technical and management factors. If critical factors can be identified and corresponding measurements can be adopted, it will be more direct and effective to improve safety performance. In this paper, by using the system thinking method, construction safety management is considered as a system and decomposed into six subsystems and related management factors. The fuzzy fault tree analysis method was used to build a reliability analysis model and reveal the failure probabilities of factors in the safety organization management subsystem. Through a questionnaire survey conducted in Wuhan, China, the pivotal importance degrees and average occurrence probabilities of basic factors are figured out. On the basis of that, nine critical factors of the safety organization management subsystem are identified and corresponding improvement measurements are proposed. More, a case study of Hangzhou underground railway tunnel collapse accident in 2008 is conducted, which verifies that the framework of construction safety management based on system thinking can be a useful tool for identifying faults or failure reasons of construction safety management.

Keywords: construction, safety management, reliability, system thinking, fuzzy fault tree.

Introduction

Construction accidents occur frequently in the construction industry, and safety management has become the top priority of construction companies and project management (Lee et al., 2012; Zhang, Fang, & Wu, 2017). According to the statistical reports released by the Ministry of Housing and Urban-Rural Development (MOHURD) of China, a total of 634 accidents occurred in the Chinese housing and municipal construction industry resulting in 735 deaths during 2016, while 692 accidents occurred resulting in 807 deaths during 2017, with an increase. Frequent construction accidents not only cause huge economic losses to construction companies, but also damage the health and well-being of relevant people and the stability of social development (Pellicer, Carvajal, Rubio, & Catalá, 2014; Feng, Zhang, & Wu, 2015).

Construction safety management is a big and complex issue with large amounts of tasks and factors. It involves systemic planning and management of various safety elements, including safety standards, safety policies, safety programs, safety evaluation, incident reporting, and incident investigation (Choudhry, Fang, & Ahmed, 2008; Hinze, Hallowell, & Baud, 2013; Haas & Yorio, 2016). Different factors, such as terrible weather, complex geological conditions, design quality, schedule, and personal professionality all have impact on safety performance (Hinze, 1997; Mitropoulos, Abdelhamid, & Howell, 2005; Han, Saba, Lee, Mohamed, & Peña-Mora, 2014). Factors of safety management are associated with the development of accident precursors, which mean "events or conditions that increase the probability of construction disruption, injuries, or deaths" (Kyriakidis, Hirsch, & Majumdar, 2012). If these factors can be effectively managed, the workplace, men, and facilities may be safe. Otherwise, bad management may lead to hazards, injuries, and accidents, thus how to establish an effective safety management framework and prevent accidents become an urgent research topic.

1. Literature review

To prevent accidents, many researches focused on causes of accidents (Heinrich, Petersen, Roos, & Hazlett, 1980;

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Suraji, Duff, & Peckitt, 2001; Khan, Suguna, & Raghunath, 2015). Through that, the main causes were attributed to unsafe human behavior and unsafe object condition, thus, these two aspects especially unsafe human behaviors became hotspot issues (Haslam et al., 2005; Hinze, 2006). Moreover, some researches revealed that unsafe worker actions were not deliberate safety violations, but rather outcomes resulting from poor hazard recognition and safety risk perception (Albert, Hallowell, & Kleiner, 2009; Tixier, Hallowell, Albert, van Boven, & Kleiner, 2014). Since the ability of hazard recognition and safety risk perception was determined in large part by safety training (Namian, Albert, Zuluaga, & Behm, 2016), construction safety management began to contain more deep-rooted factors, such as safety training, safety culture, safety climate, and so on (Wilkins, 2011; Wu, Song, Wang, & Fang, 2015; Zhang et al., 2017). Furthermore, with the rapid development of information technologies, it was also explored how to improve construction safety management by harnessing emerging technologies, such as BIM, RFID, VR and AR (Yi, Zhang, & Calvo, 2015; Lee et al., 2012; Li, Yi, Chi, Wang, & Albert, 2018).

The topic of critical factors identification of construction safety management has been always followed with interest and discussed from different levels of contractor, project, and worker team. Hinze and Gambatese (2003), Teo, Ling, and Chong (2005), and Karakhan, Rajendran, Gambatese, and Nnaji (2018) discussed about how to improve safety management of contractors. Fang, Xie, Huang, and Li (2004), Ng, Cheng, and Skitmore (2005), Aksorn and Hadikusumo (2008), Khan et al. (2015), and A. H. Memon, Soomro, N. A. Memon, and Abassi (2017) tried to explore how to effectively organize safety management and achieve good safety performance of construction projects. While Mitropoulos and Memarian (2012), and Zhang, Liu, Wu, and Skibniewski (2016) concentrated mainly on how to build cautious, rigorous, and skillful worker teams. These researches and findings are shown in Table 1.

Based on the identification of critical factors, corresponding measurements can be proposed. Cheng, Ryan, and Kelly (2012) stated that written safety policies, accident investigation and reporting, and safety records (a formal record of safety information for communication and sharing among safety parties) are most effective means of maintaining worksite safety. In contrast, Sun, Fang, Wang, Dai, and Lv (2008) reported that emergency response planning and contractors' commitment to safety had a high impact on safety performance during the construction projects of the 2008 Beijing Olympic Games. Furthermore, Costella, Saurin, and Guimarães (2009) and Subramanyan, Sawant, and Bhatt (2012) demonstrated that safety values shared by all management levels and safety commitment by all worksite personnel considerably improved safety performance. Along with the development of information technologies, Yi et al. (2015) and Li et al.

Table 1. Researches on critical factors identification of construction safety management

Researcher	Level	Critical factors
Hinze and Gambatese (2003)	Contractor	(1) Training with the assistance of contractor associations; (2) Implementing employee drug testing; (3) Minimizing worker turnover; (4) Poor management commitment; and (5) Insufficient safety knowledge and training of workers
Teo et al. (2005)	Contractor	(1) Inadequate company policies; (2) Unsafe practices; (3) Poor attitudes of construction personnel
Karakhan et al. (2018)	Contractor	(1) Safety leading indicators; (2) Safety lagging indicators; (3) Safety and supervisory personnel; (4) System maturity and resiliency; (5) Preconstruction services; (6) Technology and innovation; and (7) Safety culture
Fang et al. (2004)	Project	(1) Safety inspection; (2) Safety meeting; (3) Safety regulation enforcement; (4) Safety education; (5) Safety communication; (6) Safety cooperation; (7) Management-worker relationship; and (8) Safety resources
Ng et al. (2005)	Project	(1) Project management commitment; (2) Hazard management; (3) Safety training; and (4) Review of safety requirement in subcontractor's selection
Aksorn and Hadikusumo (2008)	Project	(1) Management support; (2) Appropriate safety training; (3) Teamwork
Khan et al. (2015)	Project	(1) Safety awareness; (2) Safety training; (3) Regular safety audit; (4) Lack of knowledge of workers; and (5) Lack of knowledge of the work
Memon et al. (2017)	Project	(1) Safety awareness and leadership; (2) Technical guidance in construction operations; (3) Technological innovation to improve safety; (4) Strictly defined operational procedures; and (5) Safety awareness of project managers
Mitropoulos and Memarian (2012)	Worker team	(1) Team cognitive attributes; (2) Team motivational attributes; (3) Team behaviors; and (4) Enhancing effectiveness
Zhang et al. (2016)	Worker team	(1) Knowledge and skills; (2) Individual differences among workers; (3) Management-oriented supervision and system; (4) Organizational climate; (5) Psychological workers' condition; (6) Workplace conditions; (7) Employee empowerment; and (8) Leadership

(2018) put forward that the application of digital technologies, such as BIM and VR/AR, could avoid errors caused by human subjectivity and establish more effective construction safety management framework.

Generally, current researches have made great progress in different levels (contractor, project, and worker team) and different aspects (behavior safety, hazard management, information technologies application, etc.) of construction safety management. Based on the previous researches, this paper explored how to comprehensively classify factors of construction safety management by using the system thinking method, and how to identify critical factors so as to guide safety management in practice. First, a model of construction safety management system was built, after the identification, classification, and integration of various factors. Then, the fuzzy fault tree method was used to identify critical factors of the safety organization management subsystem as an example. Finally, a questionnaire survey was conducted in Wuhan, China to obtain empirical data about construction safety organization management, so as to identify critical factors and propose corresponding measurements.

2. System thinking of construction safety management

2.1. Principles of system thinking

System is composed of more than two elements that are organically connected and interact with each other, with a specific function, structure and environment (Fuenmayor, 1991; Churchman, 1999). System thinking is a structural and dynamic thinking way that focuses on system structure, system behavior, and multi connection among system elements forming a purposeful whole (Stave, 2002; Goh, Brown & Spickett, 2010; ANSI, 2012). System thinking can be a useful method to describe the various factors of construction safety management and analyze their correlations. To use the system thinking method and build the model of construction safety management system (CSMS), the following principles are adopted:

1. Project phases selection. Safety management goes through the whole project lifecycle, from design to maintenance phase (Martínez-Aires, López-Alonso, & Martínez-Rojas, 2018), but tasks and requirements of safety management change during different phases. Among them, the construction phase and corresponding onsite management contain large amounts of factors including man, machine, material, construction method, and environmental impact. Therefore, the construction phase has complexity, uncertainties, and large numbers of safety risks, and need special consideration.
2. Project participant selection. Safety management needs the contribution and cooperation of different project participants, so it is a team work. Thus, project participants and their interaction among each other form a complex organization network, and coordination becomes a difficult work. To make the organization network simpler and clearer, it is necessary to focus on the major project participants, which are the owner and contractor. Besides, the government is involved during accident handling processes.
3. Decomposition and simplification. Decomposition and integration are basic analysis methods of system thinking, and are always used to resolve big and complex issues. Safety management is just such a big and complex issue and needs to be implemented step by step. Safety management contains several aspects about organization, technologies, resources, training, and emergency handling. Thus, construction safety management can be considered as a system and divided to several subsystems and then to detailed factors.

2.2. Structure of the CSMS model

Construction safety management is a typical systematical issue and contains various types of factors. In China, the major factors of construction safety management are classified as man, machine, material, method, and environment, normally abbreviated as 4M1E. These aspects are actually correlated with each other. Based on the principles of system thinking, construction safety management can be regarded as a system and decomposed to six subsystems, which are organization management, technical management, resource management, safety training, safety supervision, and emergency management. These subsystems cover different aspects of management factors, and also consider the correlations among different aspects, as shown in Figure 1. The reasons of the decomposition are as follows:

1. Organization Management is considered as the first subsystem of construction safety management. Organization is an important aspect of any management issue and cares about Man. The issues of duty allocation, leading, coordination, performance assessment, and incentive all belong to the organizational aspect. The organization for safety management normally has a hierarchical structure with several levels, such as the top management of contractor, project management team, and worker team. Improper safety organization management always leads to unsafe behavior of workers, unsafe condition of equipment, environment risks, and finally causes accidents.
2. Technical Management is considered as the second subsystem of construction safety management, including issues of Method and Environment. Method means construction technologies, processes, construction plans, and specifications. Environment means natural or social environmental impacts on safety, such as weather, temperature, working space, underground geological conditions, and so on. In this subsystem, construction plan making, hazard identification, and hazard elimination are major tasks.

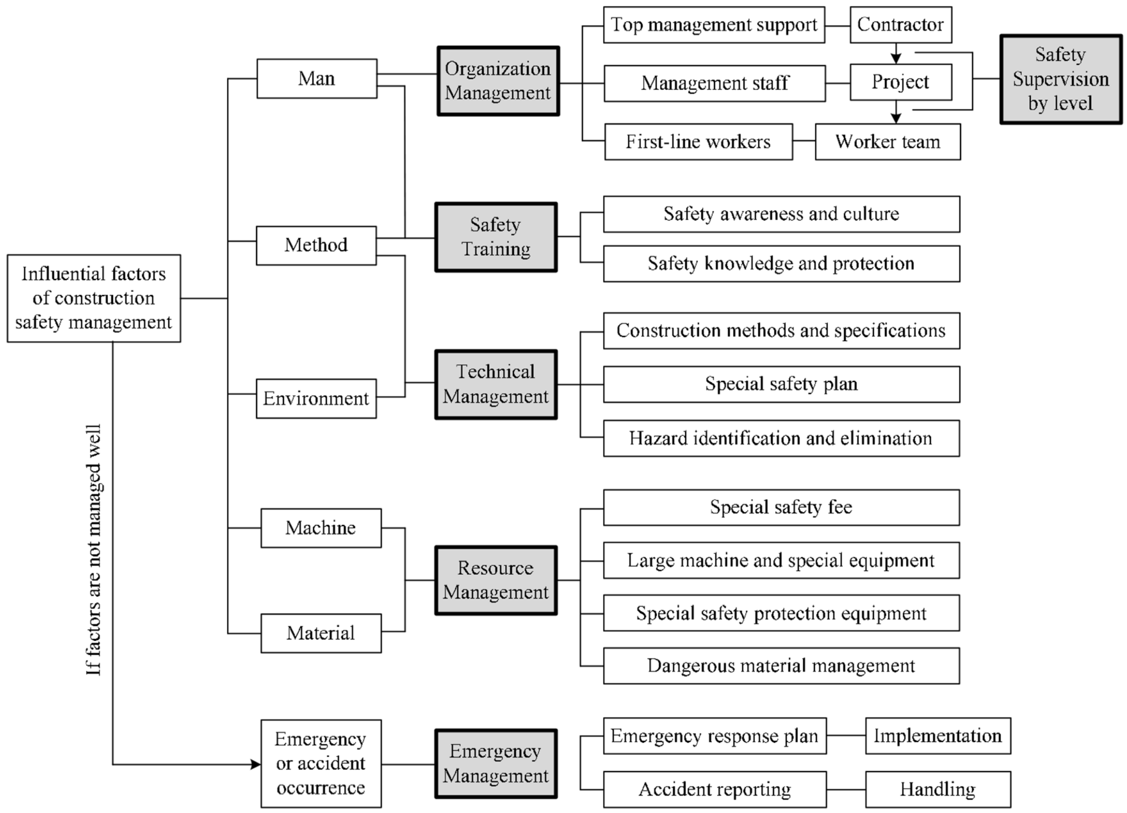


Figure 1. Structure of system thinking of construction safety management

3. Resource Management is considered as the third subsystem of construction safety management. The influential factors of Machine and Material can be jointly called as Resources. Resources such as the special fee, construction materials, mechanical equipment, and personal protective equipment (PPE) are not only needed during the normal construction processes, but also necessary conditions for ensuring the safety of workers. Inadequate safety resources or improper resource management may cause bad safety performance.
4. Safety training promotes safety awareness, knowledge, and regulate people's behavior, and then improve the identification and elimination of the hazards of unsafe human behavior, unsafe object condition, and unsafe environmental factors. Besides, safety training enhances the understanding and implementation of construction plans and specifications. Therefore, Safety Training is a necessary part of the organization issues, and also build a bridge between the organizational and technical management, thus is considered as the fourth subsystem.
5. Safety Supervision by Level is considered as the fifth subsystem of construction safety management. As the organization of safety is divided to three levels of contractor, project, and worker team, safety management should also be executed in the three levels. The levels are not parallel, but in different height. Higher levels provide support, motivation, as well as supervision to lower levels. The major supervision methods including safety meeting, inspection, reporting, assessment, and incentive should be effectively utilized.
6. Besides the management of man, machine, material, method, and environmental factors, another issue about emergency response should not be ignored. If those factors cannot be properly managed, hazards may accumulate and emergency incidents or accidents may occur. Then quick and effective responses and handling must be provided. Thus Emergency Management is considered as the sixth subsystem of construction safety management.

2.2.1. Safety organization management

As well-known, Organization is an important factor of any management issue. Different types of human resource, from top management to workers, in-office or on-site, should be well organized towards the same objective of safety. Clarifying the relationships among various elements in safety organization management subsystem can provide organizational guarantee for the effective operation of CSMS (Sawacha, Naoum, & Fong, 1999). Hereafter, three aspects are considered. First, a special department of safety management should be set, safety management duties should be allocation among the special department and other departments, and all departments should perform their safety management duties. Second, all management staff and labor should be cautious and skillful. Management staff should perform their safety management duties, and labor should act in safe ways. Third, a series of safety management regulations should be estab-

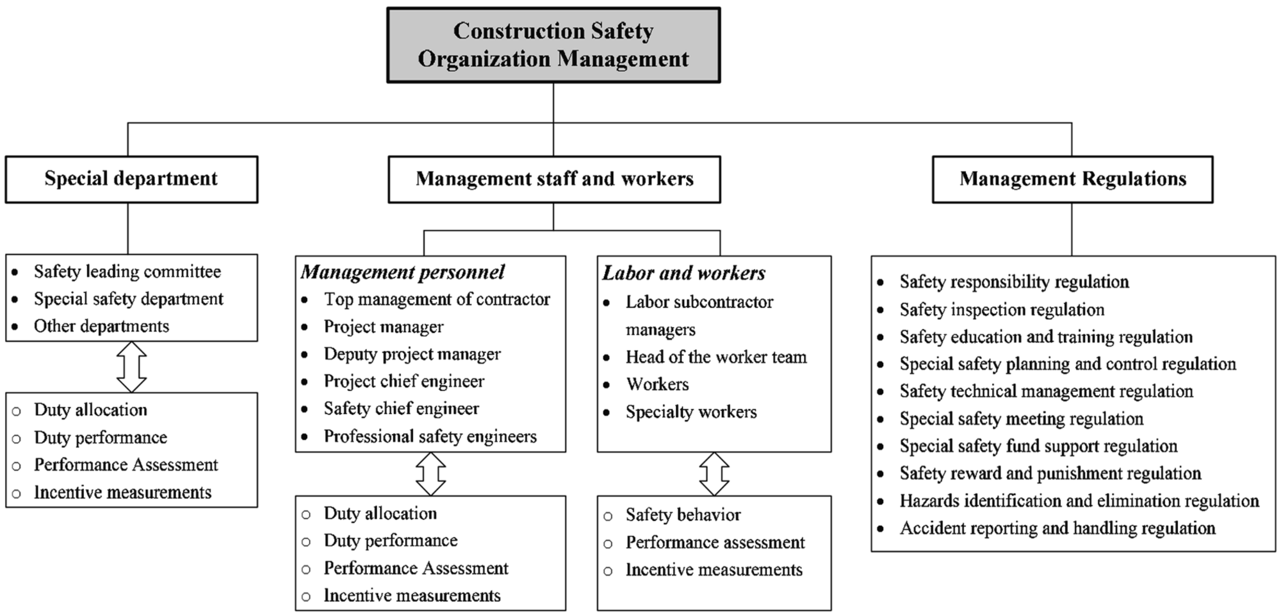


Figure 2. Structure of the safety organization management subsystem

lished and implemented according to the requirements of the Chinese *Production Safety Law* and other laws. The structure of the construction safety organization management subsystem is shown in Figure 2.

2.2.2. Safety technical management

Construction is a highly professional industry with various types of technologies application such as structural theory, mathematics, physics, material science, etc., thus technical management should be considered as the basis of safety management. The safety technical management subsystem contains three main aspects. First, different types of hazards should be pre-identified, discovered through inspection, and eliminated soon once some of them appear. Second, the project management team and special safety engineers should make special safety plans (SSPs) for the special types of construction task with complexity and high risk, such as earthwork excavation, formwork system, etc. Third, the project management team and workers should implement SSPs and create a solid techni-

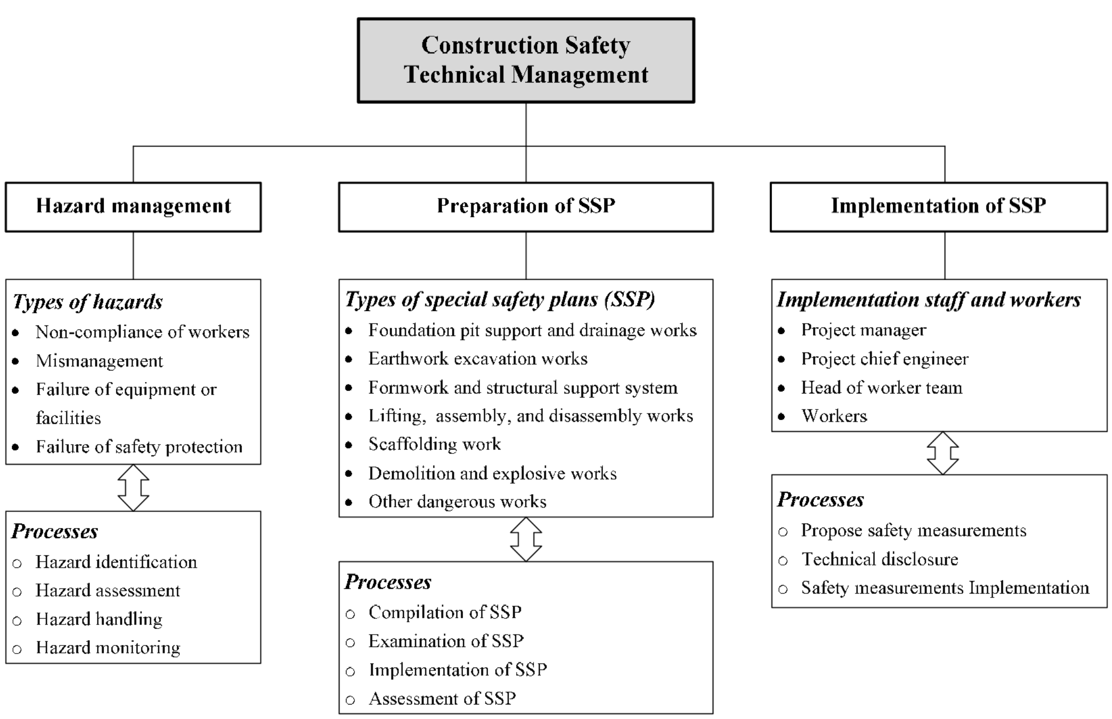


Figure 3. Structure of the safety technical management subsystem

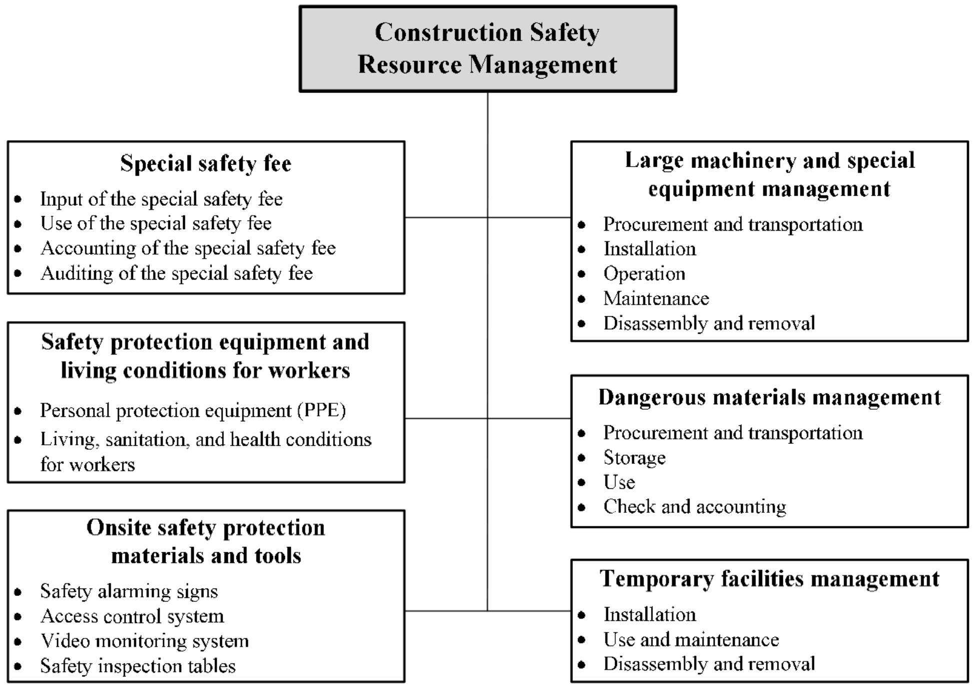


Figure 4. Structure of the safety resource management subsystem

cal foundation for safety management. The structure of the construction safety technical management subsystem is shown in Figure 3.

2.2.3. Safety resource management

Adequate safety protection and other related resource can provide a strong support for construction safety management (Han et al., 2014). Normally, safety resources contain the special safety fee, safety protection equipment and living conditions for workers, onsite safety protection materials and tools, large machinery and special equipment. The special safety fee should be input by the owner and used by the contractor only for the safety purpose, which is required by the Chinese *Production Safety Law*. Safety protection equipment, especially personnel protection equipment (PPE) such as safety helmet, safety belt can sometimes save workers' lives. Living conditions also affect workers' safety indirectly. Onsite protection materials and tools are necessary for creating an ordered construction site, for example, safety alarming signs remind people to wear PPEs and abandon unsafe behaviors, and video monitoring system help management staff discovering and stopping workers' unsafe behaviors so as to prevent injuries. Large machineries and special equipment are hard to operate and control, and sometimes bring danger to workers nearby, thus the processes of procurement, operation, and maintenance should be strictly managed. Besides, dangerous materials and temporary facilities need to be managed properly. The structure of the safety resource management subsystem is shown in Figure 4.

2.2.4. Safety training

Safety training can improve safety awareness, knowledge, and skills of both management staff and workers, thus is a fundamental part of safety management (Jannadi, 1996). Safety awareness has different meanings in different levels, including safety culture of contractor, safety climate of project, and safety awareness of staff and workers. Safety training should cover all types of people, including the top management of contractor, management staff of project, and workers. And safety training should teach various kinds of knowledge, including safety laws, technologies, protection, emergency response, and rescue. Furthermore, safety training should be well organized so as to achieve good effect. The structure of the safety training subsystem is shown in Figure 5.

2.2.5. Safety supervision by level

Safety management is implemented on different levels including worker team, project, and contractor, which form a hierarchical supervision structure. From the worker team level, safety meeting and accident prevention are two basic requirements. From the project level, special safety inspection and meeting, daily check by safety engineers, and safety performance reporting by the project team should be made, so that the project team can know and promote the safety situation of worker teams. And from the contractor level, a regular supervision mechanism of inspection, assessment, reporting, and incentive should be established, so that the top management of contractor can know and promote the safety situation of projects. The supervision mechanism is important, since lower levels such

Figure 5. Structure of the safety training subsystem

the worker team usually have weaker safety awareness, education, and knowledge. Therefore, the supervision from project can push worker team to improve safety situation. Similarly, the supervision from contractor can push project to improve safety situation. The structure of construction safety supervision subsystem is shown in Figure 6.

2.2.6. Safety emergency management

Besides the management of various factors, it is necessary to improve the ability of accidents alarming and prevention (Sun et al., 2008; Cheng et al., 2012). Meantime, it is important to minimize the injuries and property to a large extent as possible after the occurrence of emergency incidents or accidents. Safety emergency management contains two parts. First, the project team should make special emergency plan, set emergency response organization, and conduct practices about emergency response. Second, the project team should quickly report to the contractor, then to the government layer by layer once an accident happens. After that, an investigation team should

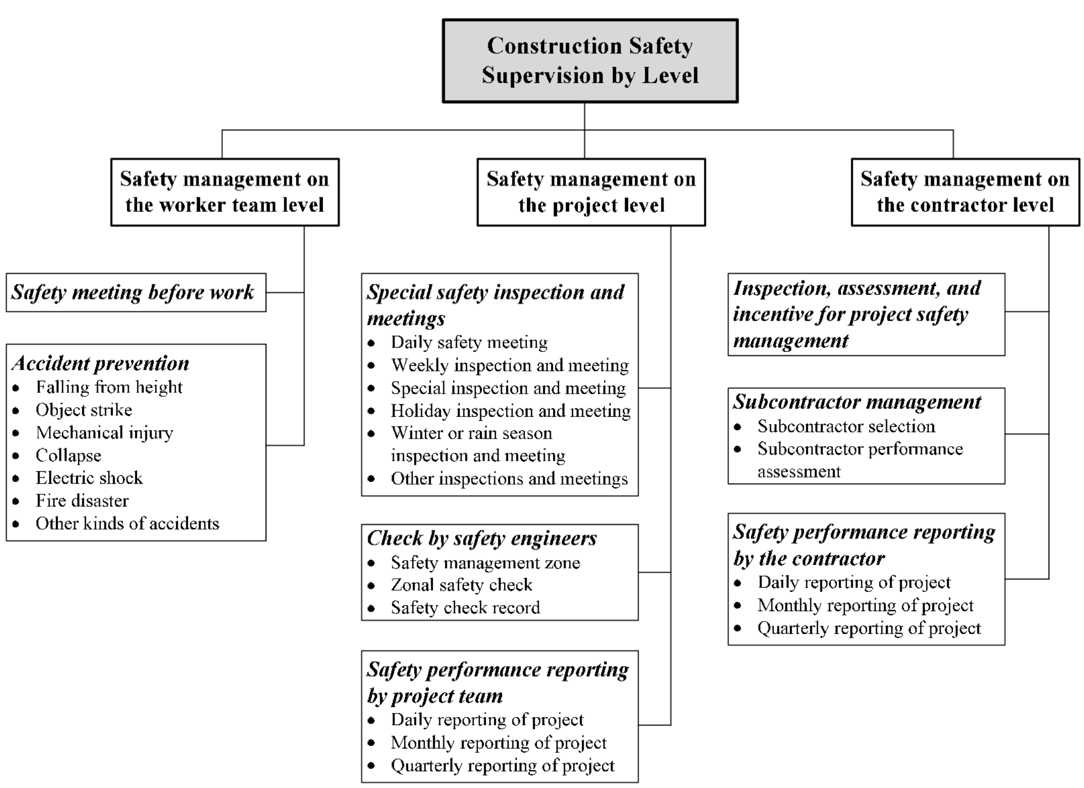


Figure 6. Structure of the safety supervision subsystem

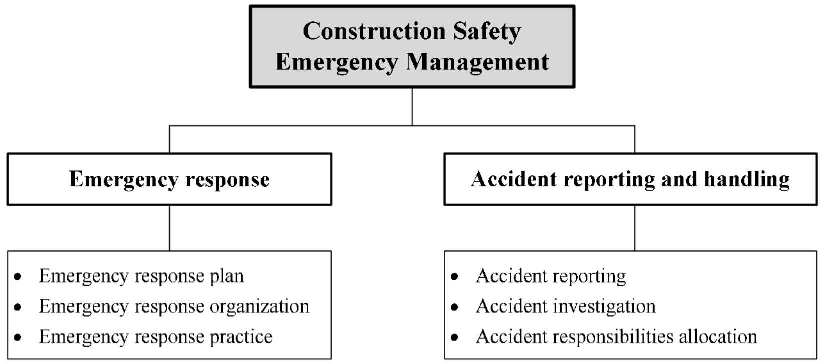
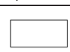
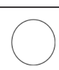
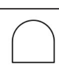


Figure 7. Structure of the safety emergency management subsystem

be organized by the owner, or by the government if the accident is serious. The investigation team should examine the accident site, discover the reasons, and proposed suggestions for responsibility allocation among related project participants and practitioners. The structure of the construction safety emergency management subsystem is shown in Figure 7.

3. Reliability model of the safety organization management subsystem

Table 2. Symbolic notations used in the fault tree method

Symbol	Name	Usage
	Event	Top and intermediate positions
	Basic event	Bottom positions
	AND gate	Intersection of two or more events
	OR gate	Union of two or more events

Based on the established CSMS model, the safety organization management subsystem is selected as an example to analyze the failure reasons and evaluate the reliability of safety management by using the fault tree method, which is a normal method for the identification of failure paths and critical elements (Lebeau & Wadia-Fascetti, 2007). The defects of management is considered as fundamental accident causes during the fault tree analysis processes, while the problems concerning natural environment, unexpected events, and other factors are excluded. The reliability model is built as shown in Figure 8. The top event numbered as T_1 represents "Failure of safety organization management subsystem", while events A_1, A_2, and A_3 represent "Fault of special department", "Fault of management staff and workers", and "Failure of management regulations" respectively. Events A_i are decomposed into events B_i, C_i, D_i, and X_i layer by layer. And the events in the bottom numbered as X_i are called basic events.

The same level of the events that intersect to trigger an upper event are articulated through AND gates, which represent the multiplication rule of probability, and all possible defective-act events are articulated through OR gates, which represent the addition rule of probability.

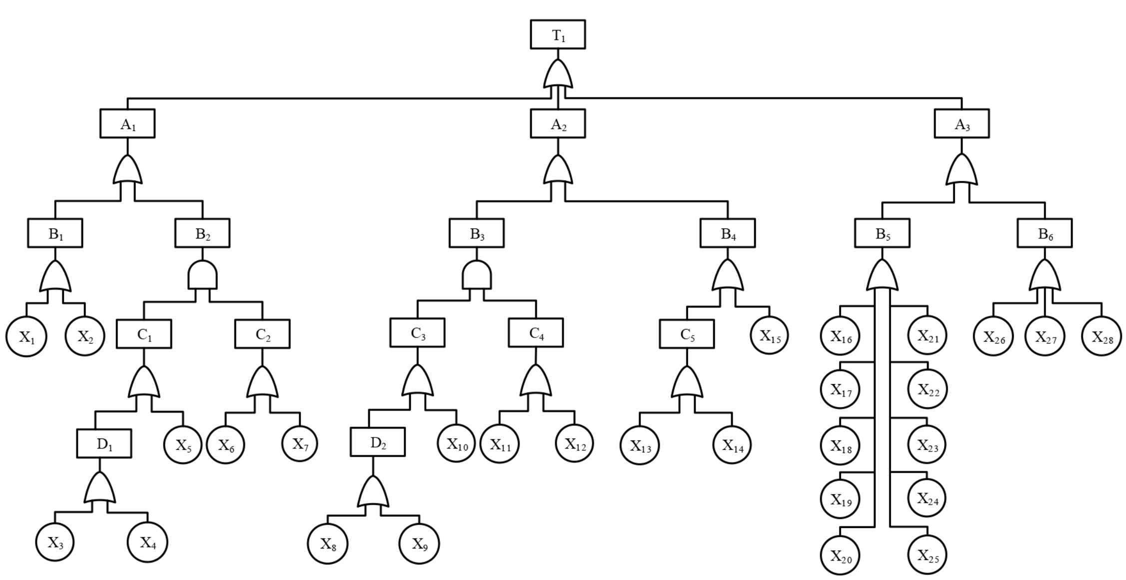


Figure 8. Fault tree of the safety organization management subsystem

Table 3. Name of event in the fault tree

No.	Name of event	No.	Name of event
	Top event	X_5	Bad duty performance of safety department
T_1	Failure of safety organization management subsystem	X_6	Lack of performance assessment for safety department
	Intermediate events	X_7	Lack of incentive for safety department
A_1	Fault of special safety department	X_8	Unclear duty of safety engineer
A_2	Fault of management staff and workers	X_9	Lack of cooperation between safety and other engineers
A_3	Failure of management regulations	X_{10}	Bad duty performance of safety engineers
B_1	Organization structure	X_{11}	Lack of performance assessment for safety engineers
B_2	Department performance	X_{12}	Lack of incentive for safety engineers
B_3	Management staff performance	X_{13}	Lack of professional skills and experience for workers
B_4	Worker performance	X_{14}	Bad duty performance of workers
B_5	Regulation establishment	X_{15}	Lack of performance assessment and incentive for workers
B_6	Regulation implementation	X_{16}	Ineffective safety responsibility regulation
C_1	Department duty performance	X_{17}	Ineffective safety inspection regulation
C_2	Department performance assessment	X_{18}	Ineffective safety training regulation
C_3	Management staff duty performance	X_{19}	Ineffective safety plan and control regulation
C_4	Management staff performance assessment	X_{20}	Ineffective safety technical management regulation
C_5	Worker duty performance	X_{21}	Ineffective special safety meeting regulation
D_1	Duty assignment among departments	X_{22}	Ineffective special safety fee regulation
D_2	Duty assignment among management staff	X_{23}	Ineffective safety reward and penalty regulation
	Basic events	X_{24}	Ineffective hazard management regulation
X_1	No safety leading committee	X_{25}	Ineffective accident handling regulation
X_2	No special safety department	X_{26}	Inadequate regulation implementation
X_3	Unclear duty of safety department	X_{27}	Lack of assessment for regulation implementation
X_4	Lack of cooperation between safety and other departments	X_{28}	Lack of incentive for regulation implementation

Table 2 provides an explanation of the symbols used in the fault tree and Table 3 shows the names of all events. A total of 28 basic events are listed in the fault tree of the safety organization management subsystem.

By using the ascending method, there are a total of 30 minimum cut sets, namely $\{X_1\}$, $\{X_2\}$, $\{X_3, X_6\}$, $\{X_3, X_7\}$, $\{X_4, X_6\}$, $\{X_4, X_7\}$, $\{X_5, X_6\}$, $\{X_5, X_7\}$, $\{X_8, X_{11}\}$, $\{X_8, X_{12}\}$, $\{X_9, X_{11}\}$, $\{X_9, X_{12}\}$, $\{X_{10}, X_{11}\}$, $\{X_{10}, X_{12}\}$, $\{X_{13}\}$, $\{X_{14}\}$, $\{X_{15}\}$, $\{X_{16}\}$, $\{X_{17}\}$, $\{X_{18}\}$, $\{X_{19}\}$, $\{X_{20}\}$, $\{X_{21}\}$, $\{X_{22}\}$, $\{X_{23}\}$, $\{X_{24}\}$, $\{X_{25}\}$, $\{X_{26}\}$, $\{X_{27}\}$, $\{X_{28}\}$. Each minimum cut set represents a failure path of the subsystem failure, so there are 30 potential failure paths in the fault tree.

4. Empirical study

In order to verify the practicality of the reliability model, a questionnaire survey was conducted in Wuhan, China. The fuzzy set theory is adopted to determine the occurrence probabilities of basic events in the model. The occurrence probabilities are used to calculate the failure probability of the safety organization management subsystem, and the pivotal importance degrees and average occurrence probabilities of basic events. Then, according to the ranking of pivotal importance degrees and average occurrence probabilities, critical factors of the safety organization management subsystem were identified.

4.1. Questionnaire survey

The questionnaire survey was conducted towards the construction practitioners who have been engaged in construction safety management practice or research in Wuhan, China for years. The questionnaire consists of two parts. The first part is about the personal information of respondents, such as age, sexuality, education background, working years, etc. The second part is about the respondents' opinion for the occurrence probabilities of basic events, evaluated by a five-point Likert scale, including 1, 2, 3, 4, and 5, corresponding with the evaluation of "Low", "Fairly low", "Medium", "Fairly high", and "High".

The questionnaires were sent to respondents via email. A total of 58 responses were received, of which 18 were removed due to incompleteness, and 40 effective responses were kept. The statistical distribution of personal information is presented in Table 4. As shown, 62.5% of the respondents have intermediate or higher title, 75% are professionals with more than 5 working years, and 72.5% are specialists with bachelor or higher degrees, which indi-

Table 4. Personal information of the respondents and corresponding weight values

Item		Sub-item		Number of respondents
Information	Weight w_i	Level	Weight w_{ij}	
Job title	5	Senior	5	2
		Deputy senior	4	5
		Intermediate	3	18
		Junior	2	14
		Other	1	1
Position	4	Company executive	5	3
		Project-level executive	4	5
		Company department head	3	3
		Project department head	2	16
		Other manager	1	13
Working years	3	working years ≥10	4	14
		5≤ working years <10	3	16
		2≤ working years <5	2	6
		working years <2	1	4
Education	2	Graduate student and above	5	5
		Undergraduate	4	24
		College	3	7
		High school	2	4
		Junior high school and below	1	0
Age	1	50 years old and above	4	2
		40 to 49 years old	3	8
		30 to 39 years old	2	17
		Under 30 years old	1	13

Note: i and *j* represent the number of items and sub-items. For example, "Job title" and "Position" are the first and second items. "Senior" and "Deputy senior" are the first and second sub-items of the first item "Job title". The values of weights are 1, 2, 3, 4, and 5 respectively.

cates that most of the interviewed respondents have abundant experience and professional knowledge with construction safety management. In addition, the positions of respondents range from company executive to project management staff. All of these information indicates that the sample is representative.

4.2. Data processing

4.2.1. Occurrence probabilities of basic events

The occurrence probabilities of basic events can be obtained through several calculation steps. Taking X_4 (Lack of cooperation between safety and other departments) in the reliability model as an example, the fuzzy failure rate (FFR) of this basic event can be calculated as below.

Step 1. Determination of the weight of respondent

According to the personal information of respondents, five weight items (job title, position, working year, education, and age) are considered, and each item is divided into four to five sub-items. Then, the compulsory comparison method can be adopted to give each respondent a weight value, and the weight values of all items and sub-items are shown in Table 4.

Let w_i be the weight value of item *i*, and w_{ij} be the weight value of sub-item *j* of item *i*. The initial importance degree of respondent *n* can be defined as:

$$r_n = \sum_{i=1}^{5} w_i w_{ij},\ \ n = 1,2,\cdots,40\,, \tag{1}$$

where r_n is the initial importance degree of respondent *n*.

After normalizing the initial importance degrees of the 40 respondents, the standard importance degree of respondent *n* can be defined as:

$$R_n = r_n \Big/ \sum_{i=1}^{40} r_i\ ,\ n = 1,2,\cdots,40\,. \tag{2}$$

Taking the first respondent (junior title, project department head, professional working age of 10 years, bachelor's degree, age between 30 and 39) as an example, the initial importance degree is $r_1 = 5\times2+4\times2+3\times4+2\times4+1\times2 = 40$ by Eqn (1). Similarly, other respondents' initial importance degrees can also be obtained. Using the Eqn (2), the standard importance degree of each respondent can be obtained.

Step 2. Turning the questionnaire result into a fuzzy set

The occurrence probabilities of basic events are divided into five linguistic values with five weight values, which

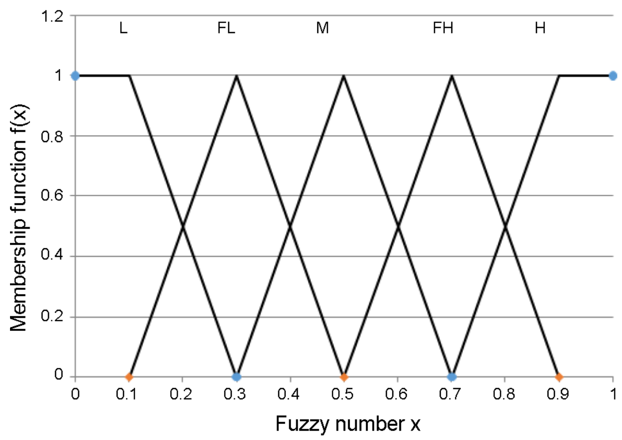


Figure 9. Fuzzy numbers of the five linguistic values

are "Low (L)" (1) , "Fairly Low (FL)" (2) , "Medium (M)" (3), "Fairly High (FH)" (4), and "High (H)" (5) . The fuzzy numbers of these linguistic values are represented in Figure 9.

The membership functions of these fuzzy numbers in triangular or trapezoidal fuzzy members are illustrated as following:

$$f_L(x)=\begin{cases}1 &, 0<x\le 0.1\\ (0.3-x)/0.2 &, 0.1<x\le 0.3\\ 0 &, \text{otherwise}\end{cases}; \quad (3)$$

$$f_{FL}(x)=\begin{cases}(x-0.1)/0.2 &, 0.1<x\le 0.3\\ (0.5-x)/0.2 &, 0.3<x\le 0.5\\ 0 &, \text{otherwise}\end{cases}; \quad (4)$$

$$f_M(x)=\begin{cases}(x-0.3)/0.2 &, 0.3<x\le 0.5\\ (0.7-x)/0.2 &, 0.5<x\le 0.7\\ 0 &, \text{otherwise}\end{cases}; \quad (5)$$

$$f_{FH}(x)=\begin{cases}(x-0.5)/0.2 &, 0.5<x\le 0.7\\ (0.9-x)/0.2 &, 0.7<x\le 0.9\\ 0 &, \text{otherwise}\end{cases}; \quad (6)$$

$$f_H(x)=\begin{cases}(x-0.7)/0.2 &, 0.7<x\le 0.9\\ 1 &, 0.9<x\le 1\\ 0 &, \text{otherwise}\end{cases}. \quad (7)$$

Step 3. Determining average fuzzy number

The evaluation results of X_4 by the 40 respondents are: 24 "L", 4 "FL", 7 "M", 3 "FH", and 1 "H". Using the α-cut method to deal with the assessment results of the 40 respondents (Lin & Wang, 1998), and combining the standard importance degrees of respondents and occurrence probabilities that the respondents evaluated in the questionnaire, the average fuzzy numbers of X_4 can be obtained:

$$W=[(0.12952+0.08024\alpha),\ (0.46753-0.19578\alpha)].$$

Let $W_\alpha=[z_1,z_2]=[(0.12952+0.08024\alpha),$ $(0.46753-0.19578\alpha)]$,

then, $\alpha=(z_1-0.12952)/0.08024$ and $\alpha=(0.46753-z_2)/0.19578$.

Thus, the membership function of average fuzzy number of X_4 is:

$$f_w(x)=\begin{cases}(x-0.12952)/0.08024 &, 0.12952<x<0.20976\\ 1 &, 0.20976\le x<0.27175\\ (0.46753-x)/0.19578 &, 0.27175\le x\le 0.46753\\ 0 &, \text{otherwise}\end{cases}. \quad (8)$$

Step 4. Converting average fuzzy number into fuzzy possibility score (FPS)

When fuzzy ratings are incorporated into FTA problem, the final ratings are also fuzzy numbers. In order to determine the relationships among them, it is necessary to convert the fuzzy numbers to crisp scores, referred as fuzzy possibility scores (FPSs). FPS represents the respondents' belief of the most possible value that an event may occur. The conversion is based on the left and right fuzzy ranking method proposed by Chen and Hwang (1992). The reason of using this method is that it is intuitive and easy to implement. In this conversion method, the fuzzy maximizing set and minimizing set can be obtained, which are defined as:

$$f_{\max}(x)=\begin{cases}x, & 0<x<1\\ 0, & \text{otherwise}\end{cases}; \quad (9)$$

$$f_{\min}(x)=\begin{cases}1-x, & 0<x<1\\ 0, & \text{otherwise}\end{cases}. \quad (10)$$

Then, by using Eqn (8), Eqn (9) and Eqn (10), the left and right FPSs of W can be obtained as:

$$FPS_R=\sup[f_w(x)\wedge f_{\max}(x)]=0.390982;$$

$$FPS_L=\sup[f_w(x)\wedge f_{\min}(x)]=0.80582.$$

After obtaining the left and right scores of W, the FPS of W is defined as:

$$FPS_T(w)=(FPS_R+1-FPS_L)/2=0.29258.$$

Step 5. Transforming FPS into fuzzy failure rate (FFR)

Most data of hardware failure rate can be obtained from a reliability data handbook. In order to ensure the compatibility between the non-fuzzy failure rate of hardware and the FPS of respondents' evaluation data, FPS must be converted into FFR. Otherwise, Lin and Wang (1998) mentioned that the occurrence possibility of a human-related subjective events is 10^{-2}–10^{-3} and the lower bound of failure rate is 5×10^{-5}. FFR can be obtained from FPS and defined as follows (Onisawa, 1988):

$$FFR=\begin{cases}1/10^k, & FPS\neq 0\\ 0 & FPS=0\end{cases},\ k=2.301[\frac{1-FPS}{FPS}]^{1/3}. \quad (11)$$

Table 5. FFRs of all basic events

Basic event	FFR	Basic event	FFR	Basic event	FFR	Basic event	FFR
X_1	1.51×10^{-4}	X_8	9.38×10^{-3}	X_{15}	2.56×10^{-4}	X_{22}	1.30×10^{-3}
X_2	1.21×10^{-4}	X_9	1.69×10^{-3}	X_{16}	9.53×10^{-4}	X_{23}	9.17×10^{-4}
X_3	2.60×10^{-4}	X_{10}	8.94×10^{-4}	X_{17}	4.52×10^{-4}	X_{24}	7.33×10^{-4}
X_4	8.16×10^{-4}	X_{11}	1.19×10^{-3}	X_{18}	7.34×10^{-4}	X_{25}	6.41×10^{-4}
X_5	1.61×10^{-3}	X_{12}	1.53×10^{-3}	X_{19}	4.95×10^{-4}	X_{26}	7.11×10^{-4}
X_6	1.45×10^{-3}	X_{13}	9.43×10^{-3}	X_{20}	6.59×10^{-4}	X_{27}	6.63×10^{-4}
X_7	2.38×10^{-3}	X_{14}	2.21×10^{-3}	X_{21}	1.08×10^{-3}	X_{28}	1.10×10^{-3}

Therefore, the FFR of X_4 can be calculated out by using Eqn (11), which is 8.16×10^{-4}, that is to say the occurrence possibility of X_4 is 8.16×10^{-4}. Similarly, the occurrence possibilities of other basic events in the safety organization management subsystem can also be obtained, as showed in Table 5. It shows that the range of occurrence possibilities in this survey matches very well with the range of occurrence possibility of human-related subjective events mentioned by Lin and Wang (1998).

4.2.2. Pivotal importance degrees of basic events

Step 1. Calculation of the failure probability of the subsystem

Due to the little occurrence probabilities of basic events in the reliability model, these basic events can be regarded as mutually exclusive events. According to the calculation formula of failure probability of the top event, the failure probability of the safety organization management subsystem can be defined as $P(T_1)=P\{\bigcup_{i=1}^{30} K_i\}$, where K_i represents a minimum cut, such as $\{X_1\}$, $\{X_3, X_6\}$. $P(K_i)$ represents the occurrence probability of K_i, which can be obtained based on the occurrence probabilities of related basic events. For example, the occurrence probability of minimum cut set $\{X_1\}$ is just the occurrence probability of basic event X_1, while the occurrence probability of minimum cut set $\{X_3, X_6\}$ is the product of occurrence probabilities of X_3 and X_6, and so on. Finally, the failure probability of the safety organization management subsystem is obtained as $P(T_1) = 2.26\times10^{-2}$.

Step 2. Importance degree analysis

The influence of each basic event on the top event is different in the fault tree. Through the importance analysis, the influence degree of each basic event on the top event as well as the whole safety organization management subsystem can be determined. In this research, pivotal importance degree is selected as a main index to determine critical factors of the safety organization management subsystem. The pivotal importance degree reflects the sensitivity of the relative change rate of failure probability of the subsystem to each basic event. Its general calculation formula is defined as:

$$I_G(i)=\frac{\partial h(P_i)}{\partial P_i}\cdot\frac{P_i}{h(P_i)},\ i=1,2,\cdots,n, \tag{12}$$

where $I_G(i)$ is the pivotal importance degree of event i, $h(P_i)$ is the probability function of the top event, P_i is the occurrence possibility of event i, and $\frac{\partial h(P_i)}{\partial(P_i)}$ denotes a partial derivative of the top event probability function for each variable.

Table 6. Pivotal importance degrees and average occurrence probabilities of basic events

Basic event	Pivotal importance degree	Ranking	Average occurrence probability	Standard deviation	Ranking
X_{13}	0.416	1	2.350	1.189	3
X_{14}	0.098	2	2.000	1.281	10
X_{22}	0.057	3	2.150	1.312	8
X_{28}	0.049	4	1.975	1.250	11
X_{21}	0.048	5	2.025	1.310	9
X_{16}	0.042	6	1.900	1.105	14
X_{23}	0.040	7	1.925	1.163	13
X_{18}	0.032	8	1.775	1.074	20
X_{24}	0.032	9	1.800	1.137	19
X_{26}	0.031	10	1.750	1.032	22
X_{27}	0.029	11	1.750	1.056	23
X_{20}	0.029	12	1.800	0.992	18
X_{25}	0.028	13	1.750	1.080	21
X_{19}	0.022	14	1.650	1.027	24
X_{17}	0.020	15	1.575	0.813	25
X_{15}	0.011	16	2.175	1.238	6
X_1	0.007	17	1.275	0.784	27
X_2	0.005	18	1.275	0.816	28
X_8	0.001	19	1.950	1.239	12
X_{12}	0.001	20	1.875	1.090	16
X_{11}	0.001	21	2.475	1.301	2
X_7	0.000	22	2.500	1.519	1
X_5	0.000	23	2.200	1.203	5
X_9	0.000	24	2.300	1.418	4
X_6	0.000	25	2.150	1.424	7
X_4	0.000	26	1.850	1.189	17
X_{10}	0.000	27	1.875	1.090	15
X_3	0.000	28	1.375	0.807	26

Table 7. Sensitive basic events in the reliability model

Selection indicator	Special department	Management staff and workers	Management regulations
Pivotal importance degree	–	X_{13} (1); X_{14} (2)	X_{22} (3); X_{28} (4); X_{21} (5)
Average occurrence probability	X_7 (1); X_5 (5)	X_{11} (2); X_{13} (3); X_9 (4)	–

According to the failure probability of the subsystem and Eqn (12), the pivotal importance degrees of all basic events can be calculated out and ranked, as shown in Table 6.

4.2.3. Average occurrence probabilities of basic events

According to the scores given by the 40 respondents, the occurrence probability of each basic event in practice is statistically calculated, and the average score F_m of the 40 respondents is used as the average occurrence probability of event m. F_m can be obtained as:

$$F_m = \sum_{i=1}^{40} c_i / 40 \,, \; m = 1, 2, \cdots, 28 \,, \qquad (13)$$

where c_i means the score of respondent i to event m, and F_m is the average occurrence probability of event m. In addition, the greater the value of F_m is, more times the corresponding basic event occurs in practice.

The average occurrence probabilities of all basic events can be calculated out and ranked, as shown in Table 6.

4.3. Problem analysis

According to the results of pivotal importance degrees and average occurrence probabilities, the basic events rank in the top five are regarded as sensitive basic events in the reliability model, which mean critical factors of the construction safety management subsystem. The top five basic events according to the ranking of pivotal importance degrees are different with the top five according to the ranking of average occurrence probabilities. The pivotal importance degree is used as the primary criterion, because it considers the respondents' professionalism and experience as weights, thus can reflect the influence degrees of factors to system more consistently with the practice. The average occurrence probability is used as a complementary criterion, because it can reflect the overall failure probabilities of different factors from the average perspective, but less reasonably without the consideration of respondents' weights. By combining the two rankings, nine critical factors are obtained, as shown in Table 7.

4.3.1. Critical factors according to pivotal importance degrees

The top five basic events according to the ranking of pivotal importance degrees are X_{13}, X_{14}, X_{22}, X_{28}, and X_{21}. Among them, X_{13} (Lack of professional skills and experience for workers) and X_{14} (Bad duty performance of workers) are both related to workers. Workers are first-line labor force on construction site, undertaking massive construction tasks and facing various safety risks. Unsafe behaviors of workers are always direct causes to construction accident occurrence. Workers must have strong safety awareness, professional skills, and experience, so that they can complete construction tasks smoothly, safely, and with good production quality.

X_{22}, X_{28}, and X_{21} are all related to management regulations. X_{22} (Ineffective special safety fee regulation) is about the input and use of the special safety fund. X_{28} (Lack of incentive for regulation implementation) revealed the implementation of safety regulations is unsatisfying, one reason for that is lacking proper incentive measurements. X_{21} (Ineffective special safety meeting regulation) is about the daily special safety meeting by the project team and worker teams, which is an important way for task assignment and communication of safety management.

4.3.2. Critical factors according to average occurrence probabilities

The top five basic events according to the ranking of average occurrence probabilities are X_7, X_{11}, X_{13}, X_9, and X_5. Except X_{13}, the other four events are different with the top five basic events according to pivotal importance degrees.

X_7 (Lack of incentive for safety department) and X_5 (Bad duty performance of safety department) are both related to special safety department. Safety department is responsible for onsite safety management, including preparing special construction plan, adopting safety measurements, conducting safety training, identifying and eliminating hazards, and handling safety problems. The duty performance of safety department directly affects the total safety situation of project, thus should be promoted through utilization of proper safety performance assessment criteria.

X_{11} (Lack of performance assessment for safety engineers) and X_9 (Lack of cooperation between safety and other engineers) are both related to management staff. Currently in practice, performance assessment and incentive are inadequate for safety management staff. Safety engineers are not fully motivated to conduct safety inspection and control throughout construction processes. Moreover, safety engineers and other types of engineers, such as quality engineers and estimators, have insufficient communication and cooperation, which is not good for building an overall strong safety climate for construction projects.

4.4. Improvement suggestions

Based on the fault tree analysis and critical factors identification, the following suggestions can be proposed for improving construction safety organization management, as shown in Table 8.

Table 8. Critical factors and corresponding improvement suggestions

Critical factor	Corresponding improvement suggestion
X_{13} (Lack of professional skills and experience for workers)	1. Set reasonable employment criteria; 2. Special safety training for workers; 3. Assistance among workers
X_{14} (Bad duty performance of workers)	1. Prepare handbook for workers; 2. Act according to the handbook
X_{22} (Ineffective special safety fee regulation)	1. Set special bank account; 2. Ensure safety purpose of the special fee; 3. Expenditure monitoring; 4. Auditing
X_{28} (Lack of incentive for regulation implementation)	1. Performance assessment for regulation implementation; 2. Top management support; 3. special safety training about regulations
X_{21} (Ineffective special safety meeting regulation)	1. Daily safety meeting; 2. Safety inspection meeting; 3. Top management support
X_7 (Lack of incentive for safety department)	1. Bonus for good performance; 2. Give honor; 3. Position promotion
X_{11} (Lack of performance assessment for safety engineers)	1. Set performance assessment criteria; 2. Conduct performance assessment
X_9 (Lack of cooperation between safety and other engineers)	1. Establish management process; 2. Communication and coordination; 3. Joint safety meeting
X_5 (Bad duty performance of safety department)	1. Prepare handbook for safety department; 2. Manage according to the handbook; 3. Reward for good duty performance

For example of X_{13} (Lack of professional skills and experience for workers), three corresponding suggestions are provided. First, contractors should set high employment criteria and try to hire cautious, healthy, skillful, and experienced workers. Second, safety trainings should be held to teach workers safety knowledge about laws and regulations, behavior requirement, safety protection, sanitation and health, first aid and recue, etc. Third, workers should help and remind each other to act in a safe way. These suggestions are also consistent with the requirements of the Chinese *Construction Law*, *Production Safety Law*, and *Regulation for Production Safety of Construction Projects*.

Among the improvement suggestions, there are several regular measurements as follows:

1. Top management support. Leadership is proven as a key factor impacting safety while practitioners are fostering proactive approaches to preventing workplace injuries (Wu, Li, & Fang, 2017). Leadership improves safety culture, and promotes safety management. Top management support is a key element of leadership. The support should cover safety meeting, safety training, personnel protection, onsite inspection, performance assessment, incentive, and other major safety management affairs.
2. Special safety training. Safety training is the most effective as well as frequently-used way to increase the safety awareness and knowledge of management staff and workers. Except for normal safety training, special training may achieve special effects, such as special training about safety laws, hazard recognition, behavior safety, safety management processes, and emergency response, etc.
3. Performance assessment. Safety management rely on the efforts of all departments, management staff, and workers. For that, performance assessment and incentive are indispensable. The criteria of safety performance assessment should be set for each department and position with essential differences. For example, for management staff the duty performance of safety management should be primarily considered, while for workers the extent of obeying technical specifications and behavior safety should be a main criterion of safety performance assessment.
4. Incentive. If management staff and workers can get reward from good safety performance, they may have more motivation to improve safety management. For workers, bonus for good performance may be mostly preferred. While for management staff, honor and chances for promotion may be more effective. Anyway, the incentive mechanism is an important part of organization management in any management field.
5. Compilation and use of handbooks. Besides getting safety knowledge from safety training, management staff and workers still need to keep learning in their daily work. Special handbooks can be very useful tools. The types of common hazards, injuries types, accidents types, personnel protection methods, emergency response, and rescue knowledge can help people on construction site. If management staff and workers can hold a handbook with such knowledges and usually read it, their safety awareness and knowledge level will be quickly improved.

4.5. Case study

On November 15, 2008, a serious accident happened in the No. 1 line of Hangzhou underground railway, Hangzhou city, Zhejiang Province, China. The underground railway tunnel being excavated and the road surface above

Table 9. Reasons and corresponding subsystems for the accident case

Level	Subsystem	Reason and description
Direct reason	Technical management	The contractor excavated the tunnel too quickly without in-time and adequate supporting facilities. The earth of the foundation pit sides fell without solid supporting structure.
	Technical management Supervision by Level	The safety monitoring system was incomplete and failed partially, onsite inspection and testing were inadequate, and thus the hazards leading to collapse were not discovered and eliminated in time.
Indirect reasons	Organization management	The contractor did not establish the institution of duty assignment and implementation for safety management. The safety department and engineers did not fully perform their safety management duties.
	Technical management	Hazards were not discovered soon. Furthermore, some discovered hazards were not quickly, completely, and substantially eliminated. Thus hazards accumulated and led to the collapse accident.
	Safety training	Safety training for workers was very weak. Even, some of the workers never received safety training, thus seriously lacked safety awareness and knowledge. They did not know when or how accidents may happen, nor how to protect themselves during the construction processes.
	Organization management	Safety management from the general contractor to labor subcontractor was loose and incomplete. The labor subcontractor and worker teams lacked professional skills and management experiences. The construction site was disordered. Unsafe behaviors of workers could be found frequently.
	Not involved in this paper	Administration from government was not strict. The Safety Supervision Station of local government did not fully perform its duty.

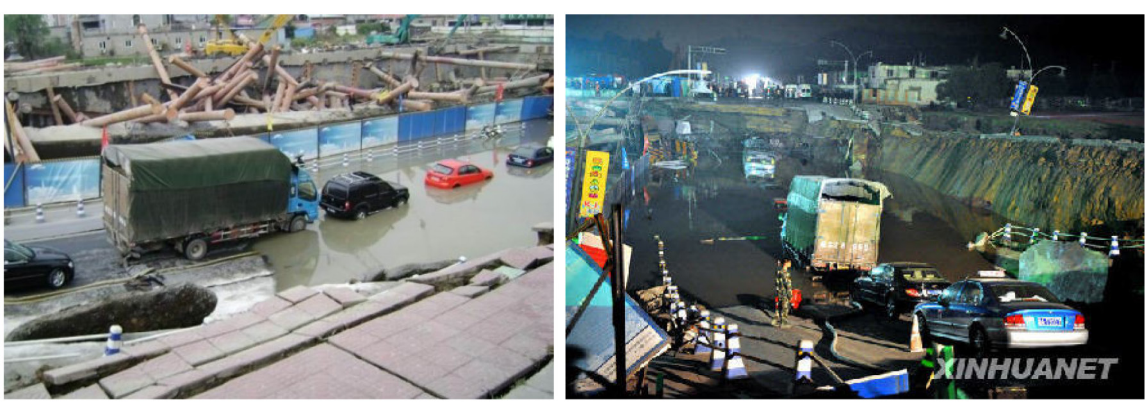


Figure 10. Onsite sceneries of Hangzhou underground railway tunnel collapse accident in 2008

collapsed. The area of collapse was nearly 100 m long and 50 m wide, where eleven buses, trucks, and cars fell in. The accident caused a very serious result of 21 deaths, 4 serious injuries, 20 minor injuries, and nearly 49 million RMB property losses. The onsite sceneries of the accident are shown as Figure 10.

After the accident happened, the Chinese Ministry of Emergency Management (MOEM), MOHURD, and the government of Zhejiang Province organized a joint investigation team. After nearly one-year investigation, the accident analysis report was issued to public in June, 2009. The report unveiled two direct reasons and five indirect reasons, as shown in Table 9. The indirect reasons are also deep underlying reasons. It is clear that most reasons belong to the six subsystems. Thus, the proposed CSMS model based on system thinking can be a useful tool for identifying faults or failure reasons of construction safety management.

Conclusions and future work

Through the system thinking, questionnaire survey, and statistical analysis of construction safety management, the following findings can be concluded:

1. By using system thinking, according to the "system-subsystem-factors" layer, construction safety management can be considered as a system and divided to six subsystems, then the subsystems can be decomposed into management factors. The six subsystems are safety organization management, technical management, resource management, safety training, safety supervision, and emergency management. The

fault tree method can be used to build a reliability model of construction safety management and evaluate the influence degrees of factors to the safety organization management subsystem.
2. Through a questionnaire survey and statistical analysis, the pivotal importance degrees and average occurrence probabilities of factors as well as basic events were calculated out and ranked. Nine critical factors of the safety organization management subsystem are identified as: X_{13} (Lack of professional skills and experience for workers); X_{14} (Bad duty performance of workers); X_{22} (Ineffective special safety fee regulation); X_{28} (Lack of incentive for regulation implementation); X_{21} (Ineffective special safety meeting regulation); X_7 (Lack of incentive for safety department); X_{11} (Lack of performance assessment for safety engineers); X_9 (Lack of cooperation between safety and other engineers); and X_5 (Bad duty performance of safety department). These critical factors reflect the weak aspects in the practice of safety organization management.
3. According to the related safety laws, regulations, and practice, corresponding improvement suggestions are proposed for the nine critical factors. Five regular measurements are strongly recommended, including top management support, special safety training, safety performance assessment, incentive for good safety performance, and compilation and use of handbooks. These measurements can improve the safety awareness and knowledge level of management staff and workers, thus improve construction safety organization management.
4. A serious collapse accident of Hangzhou underground railway tunnel occurred in 2008 was used for case study. The two direct reasons and five indirect reasons are mostly involved in the six subsystems of construction safety management. The result of case study shows that the CSMS model based on system thinking can be a useful tool for identifying faults or failure reasons of construction safety management.

There are some limitations in this research. First, due to the complexity and large amount of factors of construction safety management, only the safety organization management subsystem was used for empirical study. Since the other five subsystems, namely, technical management, resource management, safety training, safety supervision, and emergency management are also important, they need to be included in the future study. Then, the establishment of fault tree model and evaluation of occurrence probabilities are affected by the understandings and experiences of the authors or respondents, thus the results of failure probability and critical factors are just relative concepts for comparison. Last, the questionnaire survey was conducted in Wuhan, China, thus can only reflect the safety situation of a single area. More questionnaires should be collected in more cities so as to reveal more universal principles of construction safety management in the future work.

Acknowledgements

The research was financed by the National Key R&D Program of China (2017YFC0805500) and the National Natural Science Foundation of China (Grant No. 51308240). The corresponding author was the long-term construction sector expert and a full-time faculty at Huazhong Univ. of Science and Technology during the project timeline. And the questionnaire survey were supported by the experts about safety management from universities and construction companies. The authors would like to thank these supportive organizations as well as people.

Funding

This work was supported by the National Key R&D Program of China under Grant 2017YFC0805500; and the National Natural Science Foundation of China under Grant No. 51308240.

Author contributions

Wei Zhang and Xiao Zhang conceived the study and were responsible for data collection, analysis and paper writing. Xiaowei Luo was responsible for literature review, while Tingsheng Zhao was responsible for data interpretation.

Disclosure statement

We declare we don't have any competing financial, professional, or personal interests from other parties.

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