

# A taxonomy of performance shaping factors for shield tunnel construction

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## Abstract

**Purpose** – On shield tunnel construction (STC) site, human error is widely recognized as essential to accident. It is necessary to explain which factors lead to human error and how these factors can influence human performance. Human reliability analysis supports such necessity through modeling the performance shaping factors (PSFs). The purpose of this paper is to establish and validate a PSF taxonomy for the STC context.

**Design/methodology/approach** – The approach taken in this study mainly consists of three steps. First, a description of the STC context is proposed through the analysis of the STC context. Second, the literature which stretch across the PSF methodologies, cognitive psychology and human factors of STC and other construction industries are reviewed to develop an initial set of PSFs. Finally, a final PSF set is modified and validated based on STC task analysis and STC accidents cases.

**Findings** – The PSF taxonomy constituted by 4 main components, 4 hierarchies and 85 PSFs is established for human behavior modeling and simulation under the STC context. Furthermore, by comparing and evaluating the performance of STC PSF and existing PSF studies, the proposed PSF taxonomy meets the requirement for qualitative and quantitative analysis.

**Practical implications** – The PSF taxonomy can provide a basis and support for human behavior modeling and simulation under the STC context. Integrating PSFs into a behavior simulation model provides a more realistic and integrated assessment of human error by manifesting the influence of each PSFs on the cognitive processes. The simulation results can suggest concrete points for the improvement of STC safety management.

**Originality/value** – This paper develops a taxonomy of PSFs that addresses the various unique influences of the STC context on human behaviors. The harsh underground working conditions and diverse resources of system information are identified as key characteristics of the STC context. Furthermore, the PSF taxonomy can be integrated into a human cognitive behavior model to predict the worker's behavior on STC site in future work.

**Keywords** Human error, Performance shaping factors, Safety behaviour, Shield tunnel construction

**Paper type** Research paper

## 1. Introduction

Shield tunnel construction (STC) is the most widely used construction method in current tunneling construction. STC is a complex, dynamic and high-risk process. The relationship among human being, machine and environment is close in STC site. Once construction accident occurs, it may bring serious consequences to workers, machines and surrounding environment. In modern construction industry, human error is considered to be the main



factor of construction accidents; more than 70 percent of accidents are traceable to human erroneous actions or human unsafe behaviors (Haslam *et al.*, 2005). The same is true for STC. Shield tunneling is a typical human-machine-environment interaction process, and human unsafe behavior is a predominant component in the causes of STC accidents. Therefore, if a deep analysis of the factors which lead to human errors can be performed, we will find an effective method to control human unsafe behaviors, and to promote the prevention of accidents for STC. One effective approach applied to identify those factors is a taxonomy of performance shaping factors (PSFs), which is used in the human reliability analysis (HRA) method. HRA is an aspect of risk analysis concerned with comprehensively identifying and analyzing the causes and consequences of human errors (Coyne, 2009). In HRA, PSFs are used to express the factors that influence human performance in a concrete scenario (Hollnagel, 1998). There are similar concepts according to various HRA methods: performance influencing factor (PIF) (Chang and Mosleh, 2007a), common performance condition (CPC) (Hollnagel, 1998), contributing factor (Mindock and Klaus, 2014) and so on. Developing PSF taxonomy is necessary for systematically analyzing the influences of the STC context on human behaviors. Moreover, the PSFs taxonomy can be used as a subset of causal factors and mechanisms through which a causal model of human behavior is constructed. And the combination of a human behavior model and associated PSFs will provide a means to realistically simulate human behavior and to explore factors that could lead to human error.

Along with the development of HRA, PSF taxonomies have been abundantly studied. The method of PSF taxonomy can be divided into two main categories: behavior mechanism-based method and system-based method. The behavior mechanism-based method develops PSF taxonomy based on human behavior mechanism. Following are the typical PSF studies that adopt the mechanism-based method. Technique for human error rate prediction (THERP) classifies PSFs for nuclear power plant (NPP) context into three categories: external PSFs, internal PSFs and stressor PSFs (Swain and Guttman, 1983). The three categories represent work situation factors, organismic factors, psychological and physiological stressor, respectively. The PSFs are used to predict human error probabilities in THERP. In CREAM model (Hollnagel, 1998), nine PSFs were presented based on the discussion of the relationship between human error modes and failure causes. For practical reasons, the context is described in terms of a limited number of factors. These nine PSFs are divided into three or four levels to represent the different control modes of operators, and the control modes determine how actions are chosen and carried out. Chang and Mosleh (2007a) construct a PIF hierarchical classification structure based on cognitive psychology, behavioral science and NPP control room observations. The PIFs are classified into 11 hierarchically structured groups and 50 PIFs, which are identified to support the IDAC model to be implemented in a computer simulation environment. In system-based method, PSF taxonomy structure contains different aspects of the context being analyzed, the related PSFs studies are as follows. Groth and Mosleh (2012) develop a PIF set by analyzing the IDAC model, PIFs from four sources of data, current HRA models and information from NPP expert workshops. The PIF hierarchy is suitable for both quantitative and qualitative HRA application. Kim and Jung (2003) construct a full set of PIF system from collecting and reviewing existing PIF taxonomies. Based on the full set of PIF, they select PIF candidates by considering the major characteristics of NPP emergency situations and the basic criteria of PIF for use in HRA. Mindock and Klaus (2014) develop PSF taxonomy for spaceflight environment. The development is influenced by software and system modeling concepts. A visual representation of the taxonomy of factors influencing human performance and health called contributing factor map (CFM) is established in this study. It provides a common language and visual reference for identifying relevant human factors and risks during a specific spaceflight task.

In the research studies which are related to PSF taxonomy, the PSFs are developed for various human-machine interaction contexts, including NPP control room, spacecraft cabin,

aircraft cockpit and hospital diagnosis room. The PSF taxonomies are so developed as to be suitable for a specific purpose and application area. While there are many similarities between the fields mentioned above and shield tunneling, there remain clear differences. On STC site, worker monitors and operates the shield machine technical system to build the tunnel structure and change the state of surrounding geological environment. And construction hazards constantly change as the surrounding geological environment changes. During the construction process, various factors affect worker behaviors, for example, frequent monitoring and operating activities, long working hours, poor underground working conditions, organizational factors, etc (Ding and Xu, 2017). These factors must be considered while developing the STC PSFs. Human, technical system and environment are tightly coupled on STC site, and the influences of technical system and environment on human behaviors vary with different STC tasks. In our studies, considering the characteristics of the STC context, we propose an STC PSF classification frame based on Kim and Jung (2003). They assumed a “human, system, task and environment” classification frame to conduct a full set of PSFs under the NPP context. The classification frame is appropriate for the description of the STC context. Furthermore, in order to address the differences between STC and other fields mentioned above, two key characteristics of STC are identified: the harsh underground working conditions and diverse resources of system information.

In this research, through dissecting the coupling among human, technical system and environment of the STC context, the diverse influences of the STC context on human behavior were analyzed. At the same time, with considering actual STC site experiences, STC task analysis, STC accident case and relevant studies, a final PSF taxonomy constituted by 4 main components, 4 hierarchies and 85 PSFs is developed, which is able to describe the STC context systematically and reasonably, and supports for analyzing the cause of human errors for the STC context. Furthermore, STC PSF taxonomy is used to meet the requirements of the human behavior modeling and computer simulation, which is used to develop a safety management tool to strengthen construction accident prevention and safety management through quantitatively predicting and analyzing the causes, processes and consequences of workers' unsafe behaviors.

The paper is organized as follows. In Section 2, the STC background information is provided. We interpret the main train of the thought that supports STC PSF development process in Section 3. In Section 4, the details of PSFs for the STC context are developed on the grounds of actual STC accident cases and relevant research, and the advantages and disadvantages of our research are discussed by comparing and evaluating the performance of STC PSF and existing PSF studies. We conclude the study with a remark and a roadmap for the future in Section 5.

## 2. Background

Shield tunneling is a complex construction method by which workers operate the shield machine to excavate and form the tunnel structure by using shield shell and segments. On STC site, workers participate in various types of task and various stages of construction according to their different functions, e.g. shield machine operator, segment assembling operator and professional engineer. Meanwhile, shield technical equipment is used in the process of STC, e.g. shield machine, segment assembling machine, crane, etc. A stable running state of the shield technical equipment guarantees the completion of the construction. The underground environment has influence on the condition of the construction directly. And the construction environment will change with the construction process and construction mission. There are a fair number of uncertainties and safety risks because of the constant change of the construction site and complex environment (Ding *et al.*, 2012; Choi *et al.*, 2004).

In order to investigate the main features of the STC context, STC processes are dissected based on the explanation above. STC is a process in which construction workers measure

the geological environment state around the tunnel, monitor and control the shield tunnel machine technical system to transform the natural environment. In starting tunneling and arrival stage, construction workers make preparations for various types of construction machinery and equipment by installing shield machine and ancillary equipment, meanwhile they reinforce the wall of starting position. In shield tunneling stage, construction workers perform multiple tasks (e.g. shield machine attitude control, earth discharge control, segment assembling and grouting reinforcement) to ensure the safety of tunneling. Shield machine tunneling and segment assembling process change the geological environment of construction; changes in construction and action of shield machine transform the operating states of shield machine technical system. Workers control shield machine after monitoring the real-time state of shield machine and geological environment. In this process, man-machine-environment are tightly coupled; these three parts are major component of STC. Due to the coupling among human, technical system and environment, the behavior of construction workers is highly correlated with the state of the construction environment and the shield machine technical system; worker behavior is influenced by multiple aspects of construction site.

Based on studies that focus on factors causing human errors of STC and other construction industries, we can get a more specific understanding of the STC context. Due to the high task load and the complexity of tasks, construction workers are more likely to feel fatigue (Sawacha *et al.*, 1999) and stress (Leung *et al.*, 2012). Poor working environment, sophisticated technology and equipment surveillance, uncertainty construction conditions (Bakke *et al.*, 2001; Špačková *et al.*, 2013; Ding and Xu, 2017) and the unpredictability results of construction tasks (Yu *et al.*, 2014) may have a negative influence on construction workers. At the same time, the types of unsafe behavior are matched with worker's work types (Ding and Guo, 2015). Technical system, environment and individual physical and psychological state in construction process could affect construction workers' behavior. Moreover, safety culture, safety behavior management (Ding *et al.*, 2014; Luo *et al.*, 2014), construction scheme (Ding *et al.*, 2012), safety training (Chen and Wang, 2015; Ding and Xu, 2017), schedule compression (Webb *et al.*, 2016) and other organizational factors have a wide impact on all STC site personnel. Overall, in order to study PSFs in shield construction scenario, more attention should be paid to the behavior of shield construction workers during the process of the interaction among workers, technical system and environment. Nevertheless, because of the complexity of worker's behavior, no single data gathering activity will be able to acquire information about all of the factors relevant to worker's behavior on STC site. It is necessary to search more information from various data resources to develop a deeper comprehension of the factors influencing human behavior of STC.

### 3. Research methodology

As has been mentioned before, in order to develop PSFs under the STC context, it is necessary to analyze the coupling among human, technical system and environment. There are constantly interactions among workers, shield machine technical system and construction environment during construction process. The occurrence of individual behavior in shield construction process cannot separate from the interaction with shield machine technical system and environment. Therefore, we analyze the main influence of the STC context to the safe behavior from the point of view of man-machine-environment interaction. And we describe the STC context based on the classification frame developed by Kim and Jung (2003). In addition, different sources are gathered to support the development of STC PSFs.

#### 3.1 The influences of the STC context on human behaviors

Man-machine-environment interaction exists in many production activities (Gordon, 1998; Shang *et al.*, 2011; Mindock and Klaus, 2014). However, there are various interactions among man, machine and environment under different contexts. As Figure 1 illustrates, in the process of shield tunneling, the interactions among man, shield machine technical system

(hereinafter referred to as technical system) and environment are close. In order to control the shield machine correctly, workers operate the technical system controller, observe the technical system display and survey construction geological environment. The controlled shield machine transforms and even damages the surrounding geological environment, and this process will lead to a complex change of the geological environment. The change will further generate a feedback to shield machine and workers. Workers make decisions for the next step according to the dynamic change of the shield machine operating state and construction geological state.

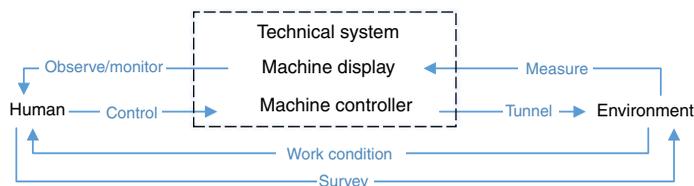
Furthermore, safety behavior appears to be significantly influenced by construction organizational factors (Sawacha *et al.*, 1999). Construction duration, resource allocation, safety incentive, onsite supervision and safety culture are part of organizational factors. Organizational factors can promote safety work behaviors by influencing individual-level safety awareness and practices (Jitwasinkul and Hadikusumo, 2011; Hsu *et al.*, 2010). Besides organizational factors, some team-related factors must be concerned. Because of frequent communication among different types of workers, STC process emphasizes teamwork and collaboration. Team communication and collaboration are the premise of an orderly and effective construction process. Therefore, STC site organizational factors and team-related factors should be considered in this research.

The above factors have effects on individual physical and mental state, and then cognitive decision-making process, eventually, individual behavior (Chang and Mosleh, 2006). Accordingly, physical and mental states of workers affect an individual behavior directly. These types of psychological and cognitive factors must be considered when identifying factors influencing human behaviors in STC site. Generally, the main influences of the STC context on individual behaviors are as follows:

- the influence of underground construction conditions on workers' physical and psychological state;
- the influence of complex technical system monitoring and operating on workers' mental state;
- the influence of STC site organizational factors on workers' safety awareness;
- the influence of continuous construction team communication and coordination on worker behaviors; and
- the influence of workers' physical and psychological states on the cognitive decision-making process of workers.

### 3.2 STC context description for PSF taxonomy

Kim and Jung (2003) assumed that the context under which an operating crew should perform given tasks can be modeled as "human, task, environment, system." At a macro level of context description for STC PSF taxonomy, the four components are human, technical system, environment and task. Human component contains different types of workers. Technical system component includes machinery or electrical equipment. The environment of STC site contains not only natural environment and artificial

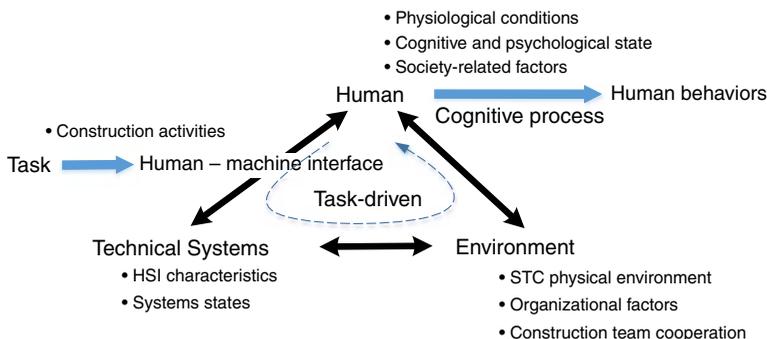


**Figure 1.**  
Human-machine-  
environment  
interaction of STC

environment, but also construction organizational environment and construction team environment. The task component is used to represent the construction activities and tasks states. The interaction of human, technical system and the environment is driven by task. Depending on the analyses above, a description of shield tunnel construction context for PSF taxonomy is presented in Figure 2. The description expresses diverse influences of the STC task context on individual behavior through analyzing the coupling among human, technical system and environment. It is an appropriate framework and guidance for developing PSFs under the STC context.

As shown in Figure 2, the STC context is composed of four components: human, technical system, environment and task. From a PSF development perspective, those components should be further analyzed in order to identify the main influences of the STC context on human behaviors. However, in the STC context, these components are different from the NPP context described by Kim and Jung (2003) or other fields mentioned above. We should address the essential differences for the STC context, the differences are manifold:

- (1) Harsh underground working conditions. As for the industries mentioned above, the main tasks of operator are monitoring and controlling machinery and equipment, they are almost performed in fixed working places (Chang and Mosleh, 2007a; Mindock and Klaus, 2014; De Ambroggi and Trucco, 2011). However, workers have to participate deeply into the construction process, not just work in a fixed place which is separated from the construction site. Compared with other industries, the underground natural environment of STC site has a significant impact on worker behavior, including physical changes due to the worker's exposure to underground working environment, and possible cognitive impacts arising as a result of limitations from working in rather harsh conditions (Bakke *et al.*, 2001; Hermanus, 2007). Moreover, the layout and the orderliness of construction site have an effect on safety performance (Sawacha *et al.*, 1999; Toole, 2002). As a result, the underground natural environment and working conditions of STC site are considered for developing STC SPFs.
- (2) Diverse resources of system information. In NPP and other industries mentioned above, operators acquire the system state information through monitoring the display equipment of machinery and equipment (Coyne, 2009; Boring, 2015). Nevertheless, the resources of system information are more diverse in the process of STC. Besides monitoring the display equipment of the technical system, workers usually need to enter into the construction site and observe the equipment operating phenomena or environment phenomena directly (Yu *et al.*, 2014). Hence, workers have to perform much more diverse tasks on account of a wider range of system



**Figure 2.**  
Description of shield  
tunnel construction  
context for PSFs  
taxonomy

state information. In conclusion, the technical system operating phenomena and the engineering geological characteristics are captured for the development of STC PSFs.

Besides the similarities between STC and the industries mentioned above, these two key features of STC have been considered while developing STC PSFs.

### *3.3 PSF development process*

In this research, STC tasks analysis, STC accidents cases and relevant PSF research are combined to support PSF development in the STC context. To begin identifying and developing detailed PSFs, it requires a lot of literature review which stretches across PSF research studies, human factors, safety behavior, cognitive psychology and actual construction data (construction schemes, and so on). Additionally, STC accidents and incidents cases are collected and analyzed to support PSF identification and verification. There are three criteria of cases selection:

- (1) The accidents must occur in the phase of shield tunneling construction. Other construction phases (e.g. construction design, maintenance, and metro station construction) are beyond the scope of our study.
- (2) The cause of the accidents must be relevant to human error. The accidents which were merely caused by geological risks or technical system failures are beyond the scope of our study.
- (3) A detailed record of the accident is essential. Even though some of the accident cases are related to human error, we could not identify the factors causing human error if the record is too sketchy. Therefore, we filter out the accident cases that lack detailed record of the accident.

According to the description of the STC context, four components of the STC context were defined: human, technical system, environment and task. And then we divided each component into several categories by analyzing characteristic of STC tasks and reviewing relevant literature. Each of these categories corresponds to different aspect of the corresponding component (e.g. human component was divided into four different categories: physical factors, memorized information, mental state and society-related factors). According to the compilation process of identified factors in Mindock and Klaus's (2014) research, as the factors that belong to a same categories grew, we began to put factors together on a same group according to their effects for human performance, such as time-constrain load, task load and passive information load. A four-hierarchy structure was built after the process. Furthermore, PSF development is an iterative process. STC accidents and incidents cases are used to modify factors until the identified factors match the real STC scenario. After identifying and modifying PSFs, a normalization process was conducted to ensure the precise definition for each factor, and to ensure that they do not overlap in definition. Figure 3 shows the process of PSF development. The detailed PSF taxonomy is elaborated in Section 4.

## **4. Results and discussion**

### *4.1 The overall structure of STC PSF taxonomy*

An overall classification structure of PSFs was built based on the "human, technical system, environment and task" description and STC task analysis. As shown in Figure 4, human component contains the human-related PSFs, such as mental state, memory, physical conditions and individual society-related factors. Technical system component refers to the characteristics of shield machine; we need to select the factors that have influences on

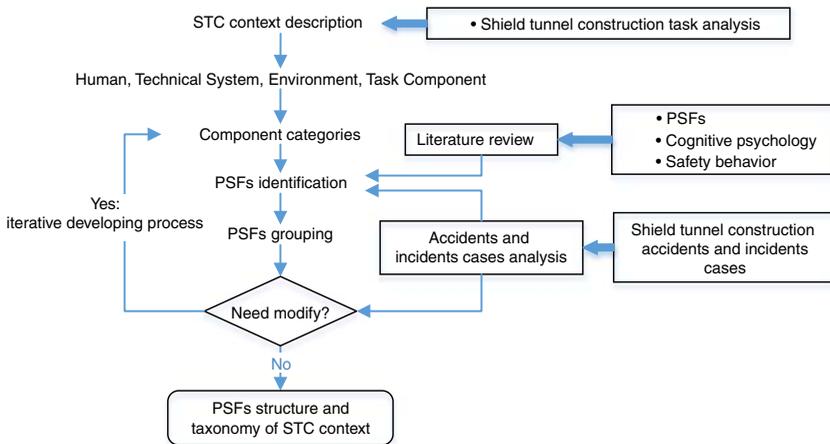


Figure 3. PSFs development process

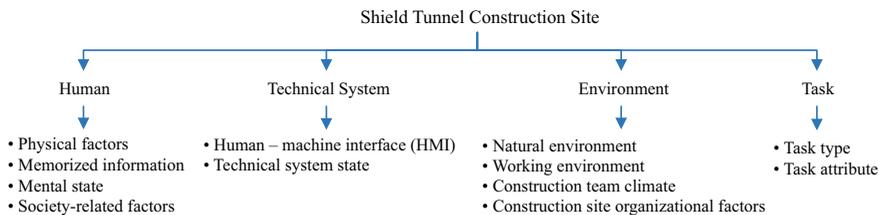


Figure 4. Overall structure of STC PSFs taxonomy

human behaviors from these characteristics. As for environment component, the environment is a general concept, which contains many aspects of STC site, such as physical environment and organizational environment. Construction task type and the abstract qualities which will directly affect human behaviors are identified.

#### 4.2 The final set of PSFs

**4.2.1 Human component.** The PSFs of human component are classified into four groups: physical factors, memorized information, mental state and society-related factors. Physical factors will impact physical functions of workers while they are performing their construction tasks. And society-related factors have a moderate effect on human behavior in construction activities (Motowidlo *et al.*, 1986). Mental state together with memory represents the operator’s cognitive and psychological states, these psychological states can dominate individual cognitive decision-making process. In aspect of cognitive factors, the PSFs related to mental factors of STC workers were built on IDAC mental state factors (Chang and Mosleh, 2007a). IDAC model probabilistically predicts the cognitive responses of the control room crew in NPP during accident conditions. Through combining various dimensions of operators’ responses including cognitive, emotional and physical activities, IDAC models operators’ cognitive process. The mental state of IDAC model covers four PIF groups that are used to represent four phases of mental activities, which are important parts of the cognitive process. There are two reasons for referencing the mental state factors of IDAC model: first, comparing with other PSF studies, the mental state factors of IDAC model provide a more precise definition in description of the cognitive process and causal mechanisms (Chang and Mosleh, 2006). The mental state factors allow, and significantly

reflect, the cognitive, emotional and physical activities of operator, although IDAC is applied for the NPP context. Second, decision making and cognition mechanisms are human characteristics; these characteristics are independent of the context. It is feasible that we develop the PSFs of human component based on IDAC mental state factors. At the same time, considering construction hazards and high workload, we pay more attention to the cognitive factors which cause stress and distraction, so that some details of the internal IDAC PIFs were modified based on actual STC task analysis. The following is the detailed PSF explanation, and necessary literature support and accidents cases are provided.

**Physical factors.** Physical factors refer to individual ergonomic characteristic and physical conditions. Age and some physical limitations (e.g. color blindness, acrophobia and hypertension) are basic requirements for some high workload tasks and special operations (e.g. aerial work, underground work and shield machine operating) (Rosekind *et al.*, 1994). Moreover, from Siu *et al.*'s (2003) research, it can be seen that some older workers have more positive attitudes toward safety, compared with younger workers. As for physical load, because of the high workload and nocturnal shift work of STC tasks, the frequency of feeling fatigue is much higher during the construction process. While performing STC activities, fatigue is a dominant factor that impacts worker's performance and induce human error (Sawacha *et al.*, 1999; Griffith and Mahadevan, 2011; Williamson *et al.*, 2011; Desmond and Matthews, 1997).

**Memorized information.** Memorized information refers to the information perceived by workers, including workers' working memory, knowledge and experience. The correctness and accuracy of individual memorized information determine the reliability of individual situation assessment and decision making (Wickens *et al.*, 2015). Memory consists of two different function parts: working memory and long-term memory (or knowledge base) (Reason, 1990; Swain and Guttman, 1983). Working memory is a dedicated system which maintains and stores information in a short term, and has a limited information capacity. In the STC context, working memory is worker's perceived information when they carry out their task. During the construction process, the decline of working memory can result in some serious human errors (e.g. omitting a necessary working procedure, omitting a crucial alarm). In contrast with working memory, long-term memory is a psychological result of perception and learning and reasoning gained through long-term construction practices, and has an unlimited information storage capacity (Wickens *et al.*, 2015). Job skill, knowledge and experience are all parts of long-term memory. The worker's unsafe behavior would be caused by lack of construction experience and knowledge in an unfamiliar construction situation (Quiñones *et al.*, 1995). Example of less experienced contributing to unsafe behavior is:

- Guangzhou metro, line 4, shield machine rollover accident[1]. Accident description: when the shield machine rolling torque was much higher than normal value, the inexperienced operator still tried to forcibly drive the cutter wheel. The wrong operation made the shield machine overturned, and damaged the cutter wheel.

**Mental state.** Mental state represents one's cognitive and emotional conditions during construction process. Mental state explains why and how a decision can be made. It defines the state of the operator's mind in various dimensions such as individual differences, situation perception and appraisal, feelings about the situation and certain cognitive behavioral modes (e.g. bias). There are four PIF groups (cognitive modes and tendencies, emotional arousal, psychological load and feelings and perception and appraisal) that represent four phases of mental activities in IDAC internal PIFs. Another group denoted as intrinsic characteristics is included in the mental state to capture the effect due to individual differences. The mental state consists of the above four PIF groups to represent the state of one's mind. For purpose of developing PSFs for the mental state category, the impact of the

STC context on individual mental state should be considered. Workers are prone to be in a state of stress because of high workload, limited construction period and poor working environment. Taking these factors into consideration, we modified some factors and keep the remaining PSFs related to high-stress and high time-constraint environments. The remaining PSFs constitute the mental state of workers in the STC context. The following is the relevant PSF groups and detailed PSFs.

Cognitive modes and tendencies group is used to represent attention and alertness level of the individual. Low alertness level or distraction might make worker miss some key information and even cause unsafe behaviors (Young and Salmon, 2012; Reason, 1990). One example of low-level attention is:

- Xi'an metro, line 2, tunnel fire accident[2]. Accident description: a welder did not notice the weld splatter during the welding work. The left weld splatter sparked off the fire.

Emotional arousal refers to the emotion inspired by psychological load. Because of the high-stress construction environment, the result of emotional arousal is a feeling of stress. In a high-stress situation, workers will suffer from fatigue and nervous, as a result, their work efficiency will decrease (Leung *et al.*, 2011). In addition to the efficiency problem, high-stress state can change individual decision-making process, most people would perform the complex and unfamiliar task in a simple but improper strategy, and human error will be easily caused under this situation (Welford, 1973; Wickens *et al.*, 2015).

Psychological load and feelings refers to the perceived mental load and subjective experience after workers perceived and assessed the situation of the STC site. Specifically, the perceived mental load includes time-constrain load, task load and passive information load, which can cause stress, distraction, fatigue and also the change of decision-making ways (Motowidlo *et al.*, 1986; Wickens *et al.*, 2015; Maule and Svenson, 1993).

Perception and appraisal refers to the worker's automatic response on information perception and situation appraisal, which is stimulated by incoming information from outside environment. This category contains perceived urgency of current situation, perceived familiarity with situation, perceived criticality of current task, perceived complexity of current task and awareness of responsibility. When a worker perceives information related to a construction task, the worker will form awareness and assessment of current situation, and the result of situation awareness and assessment will result in a series of emotional and cognitive responses (Chang and Mosleh, 2007a). An example of high level of stress is:

- Guangzhou metro, line 4, tunneling axis overrun accident (see Footnote 1). Accident description: the tunneling deviation of left tunnel exceeded the limit. At the same time, the operator found the starting foundation was deformed. In this case, the operator was in a hurry to correct the tunneling deviation, but he adopted an improper procedure to solve the problem. As a result, the reaction frame was damaged, and the horizontal displacement of the shield machine continued to increase.

Intrinsic characteristics refers to one's personality and character. People have different personality types which represent different styles of problem solving and decision making (Li, 2013). As a result, various personalities will cause different safety attitudes and motivations which might result different behaviors, even unsafe behaviors (Tett *et al.*, 1991; Hertz and Donovan, 2000; Barrick *et al.*, 2002).

Society-related factors. Society-related factors refer to the social attribute that will influence human performance. In STC site, education level and family situation are the most important social attribute of workers. Worker with higher levels of education has stronger reasoning abilities. Especially for shield machine operators, a high education level can

increase working efficiency in high cognitive load activities (Artman *et al.*, 2006). A harmonious family has a positive effect on individual emotion and feeling, which will help workers to pay more attention to their tasks (Allen *et al.*, 2000; Geurts *et al.*, 2003).

*4.2.2 Technical system component.* Technical system refers to the machinery and electrical equipment which are used in STC process (e.g. cutter wheel drive hydraulic system, shield hydraulic propulsion system, erector and grout injector). In technical system component, the system state parameters and human–machine interface (HMI) availability of shield machine have a direct effect on operator behavior in the interaction between operators and shield machine. The monitoring and controlling process of shield machine technical system brings a lot of operations and information, which will induce a high cognitive load. In STC site, the controller and display equipment are the interfaces between operators and shield machine technical system, so the design of HMI and the running states readings of shield machine are two main aspects that we should pay attention to. Furthermore, in many cases, workers need to assess the technical system status by observing the running phenomenon of critical system component on the construction site; these phenomena cannot be read from the display device. It is one of the distinctions between STC task and NPP task. There are two main categories in technical system component: HMI and technical system state.

Human–machine interface. HMI refers to points of interaction between people and the system (Swain and Guttman, 1983). The controller and displayer both belong to this category. A logical layout of controller and displayer may make operation easier through reducing operation steps (Groth and Mosleh, 2012). Furthermore, the availability of these equipment is significant; the following cases proved the influence of unavailable HMI on human behaviors:

- Guangzhou metro, line 3, segments damage accident (see Footnote 1). Accident description: there was no grouting manometer in the displayer of grout injector, and operator incorrectly estimated the grouting pressure. In this situation, the high grouting pressure crushed the segments.
- Guangzhou metro, line 3, hydraulic jack damage accident (see Footnote 1). Accident description: the controller of segment assembling machine was divided into two separated parts, so the operators controlled the segment assembling machine in two places. Because of the mismatch of the control process, the hydraulic jack was destroyed.

Technical system state. Technical system state refers to the essential information that reflects the operating state of the shield machine technical system, it includes two PSF groups: operating parameter and operating phenomena. As has been analyzed above, operating parameter denotes the operating states which can be read from the display equipment, for example, parameters state, change rate of parameter and number of parameter anomalies and alarms. Moreover, compared with the feedback of display equipment, the operating phenomenon is hard to perceive and observe. The ambiguousness and uncertainty will be caused by observing the diverse system phenomena, which have a direct influence on worker's situation awareness and decision making (Li, 2013). The technical system states directly reflect the construction safety situation which is crucial for worker's situation awareness and emotional arousal (Julius *et al.*, 1995). And they are the basis for accident diagnosis and decision making. For example, while starting up the shield machine, operator has to listen to the running sound of the hydraulic pumping system to determine whether the system is normal.

*4.2.3 Environment component.* The environment component is a general concept which consists of natural environment, work environment and intangible environment of STC site.

The environment of STC site contains natural environment, working environment, construction site organizational factors and construction team climate factors.

**Natural environment.** Natural environment refers to factors related to the geological environment and meteorological conditions of STC site. Natural environment is a primary factor that will be considered first during tunneling process. On the one hand, complex geological environment may bring natural disasters to STC site. On the other hand, workers will be influenced by meteorological conditions (e.g. high temperature, high pressure, rainfall and so on) because of deep shaft which exposed to ground environment. An example of poor geological environment to error is:

- Beijing metro, line 10, collapse accident (see Footnote 2). Accident description: after a collapse of tunnel face, the workers carried out the emergency measures blindly before they made sure about the geology stability, and it caused another collapse and killed six people.

**Working environment.** Due to the characteristics of underground construction, there are more environmental restrictions than the general ground engineering. We summarize two main PSF groups to describe the environmental restrictions of the working environment of STC site. First, the orderliness of the construction site and logical site layout is a necessary condition for construction safety (Sawacha *et al.*, 1999). A disordered construction site would hinder workers from performing their tasks. Second, some special environment conditions cannot be neglected, for example insufficiency of illumination, oxygen deficiency, toxic gas, noise and so on; working in those special situations will cause harmful impacts to workers' health (Bakke *et al.*, 2001).

**Construction team climate factors.** Communication and teamwork will determine the task-performing efficiency of STC. Generally, the STC process requires collaboration and coordination among diverse types of workers. Developing clear communication and good teamwork will improve information sharing within the team, and team members can gain enough information to make the right decision. One example of inadequate team communication is:

- Shanghai metro, Line 4, water inrush accident (see Footnote 2). Accident description: the groundwater pressure had been close to the critical value, it was an important symptom of water inrush accident. However, the workers did not report the situation to managers. It was a main cause of the water inrush accident.

Moreover, leadership is also an important factor which will help workers to build confidence and increase job satisfaction. It has a positive effect on their safety behaviors (Nahrgang *et al.*, 2011). In conclusion, team collaboration, teamwork, team communication and leadership are main PSFs of construction team climate category.

**Construction site organizational factors.** The quality of construction organization management is a key part of construction organization activities in STC site. We summarized the main aspects of shield construction organizational factors (safety incentive, resource allocation, construction scheme, onsite supervision, safety training and safety culture) by reference to relevant literatures review and construction organization design of several STC project. The following is detailed PSF groups and corresponding PSFs. Construction schedule is a guidance for STC, and the construction is a time-critical process. The limited construction period can cause high time-constraint load, which is an important stressor in the STC context. An example of limited construction period to error is:

- Guangzhou metro, Guang-Fo Line, rail brackets slip accident (see Footnote 1). Accident description: because of the strict time constraint of tunneling starting, workers installed the rail brackets within a limited time. The workers were not strict with the procedure in order to expedite the installation, as a result, the rail brackets slipped and broke down.

Safety incentive has influence on safety performance of construction worker; there is strong relationship between safety incentive (e.g. productivity bonus pay, safety bonus pay) and safety performance (Sawacha *et al.*, 1999). However, the positive influence is not permanent and diminished with time (Hinze and Gambatese, 2003; Gangwar and Goodrum, 2005); hence, an effective safety incentive is necessary for promoting safe behavior on STC site. The effectiveness of safety incentive is a PSF that needs to be taken into account in the STC context.

Resource allocation provides guarantees for manpower and material resources. Reasonable task assignment and salaries, available equipment and sufficient material supply will have positive influences on workers' performance (Sawacha *et al.*, 1999; Arends *et al.*, 2005). Construction scheme is also an important organizational factor which provides special construction method and construction procedure. A correct construction scheme can help workers finish their task safely and successfully (Abdelhamid and Everett, 2000). One example of unsuitable construction scheme is:

- Shanghai metro, Line 4, water inrush accident (see Footnote 2). Accident description: water inrush accident of across channel. Workers performed their internal bypass excavation and shaft excavation task in a wrong order. Meanwhile, the reinforcement scheme was unqualified. As a result, a water inrush accident happened.

The construction supervision and inspection can prevent and correct workers' unsafe construction behaviors by ensuring construction works in compliance with the construction regulations, and supervising execution of the work (Tam *et al.*, 2004). The example of inadequate supervision to unsafe behavior is:

- Hangzhou metro, Line 1, collapse accident[3]. Accident description: because of supervisor's dereliction of duty, the worker's wrong operation has not been found and corrected. The wrong operation became one of the most important safety risks that resulted in the subsequent collapse accident.

An adequate safety training promotes the improvement of individual awareness, and safety training is an efficient way to foster safety awareness among workers (Ai Lin Teo *et al.*, 2005; Abdelhamid and Everett, 2000). Similarly, STC site safety climate has an important influence on ensuring adherence to procedures, and plays a significant role in the promotion of worker commitment and participation in safety (Fugas *et al.*, 2012; Clarke, 2006).

**4.2.4 Task component.** Task component reflects the details of the STC process and involves the specific operations of crew. STC is a complex construction process which contains a variety of construction tasks. We extract the characteristics of different types of actual construction task with a view to identifying factors which significantly affect workers behaviors. Different types of task have different influence on worker behavior. Combined with relevant PSF sets (Kim and Jung, 2003; Chang and Mosleh, 2007a) and STC task analysis, we extract the main characteristics of STC task to develop the PSFs of task component.

**Task type.** Workers could perform multiple types of tasks in multiple construction stages on STC site. For example, in shield tunneling stage, worker might need to monitor system states changes on multiple indicator boards simultaneously. However, in the segment assembling process, workers need to operate the segment assembling machine to form the tunnel structure. Different tasks have different requirements for worker's physical ability and experience, and high task requirement could cause feeling of fatigue and stress.

**Task attribute.** Task attribute category includes task urgency, task hazards, task load and task consequence. Task urgency, hazards and severity of task consequence are all sources of job stress during construction. Workers may make unsuitable decisions under

urgent and dangerous situation (Brough and Williams, 2007; Cohen, 1980). The example of high task urgency to unsafe behavior is:

- Guangzhou metro, Line 4, tunneling axis overrun accident (see Footnote 1). Accident description: the example of high task urgency to unsafe behavior is: the tunneling deviation of left tunnel exceeded the limit, at the same time the starting foundation deformation was found. The situation was very urgent because the consequences would likely be very severe, so the operator was in a hurry to correct the tunneling deviation in this situation, but he adopted an improper procedure to solve the problem. As a result, the reaction frame was damaged, and the horizontal displacement of the shield machine continued to increase.

Task load has a significant impact on human performance. Because of the long construction hours and complex tasks, STC process often brings high task load to workers. High task load will cause fatigue and stress, so that it will have a negative influence on workers' behavior (Recarte and Nunes, 2003; Olivers and Nieuwenhuis, 2006).

According to the analysis and discussion, we develop the PSFs with a hierarchical structure, which will help us to present the STC PSFs reasonably and clearly. As shown in Table I, the final set of PSFs contains 4 main components, 4 hierarchies and 85 PSFs.

### 4.3 Discussion

Based on the classification principles proposed by Groth and Mosleh (2012) and Kim and Jung (2003), we compare the performance of STC PSF taxonomy with existing typical PSF taxonomies. The aim of the comparison is to evaluate the performance of STC PSFs and to learn areas that require improvements. The PSFs in THERP (Swain and Guttman, 1983), CREAM (Hollnagel, 1998), IDAC (Chang and Mosleh, 2007a) and CFM (Mindock and Klaus, 2014) are considered. The detailed comparisons are discussed in the following four classification principles.

*4.3.1 Highlighting the context features.* A main function of PSFs is to give an appropriate description for the context. The taxonomy should include all the important factors to assess overall task context as comprehensively as it can, and the PSFs should be as specific and practical as possible (Kim and Jung, 2003).

THERP describes the details of the task context through a detailed discussion and examples of many of the specific PSFs applied in NPP operations, and those PSFs that highlight the working conditions, task and equipment, job and instructions, psychological and physiological stressor are identified. In CREAM, working conditions, adequacy of organization, adequacy of man-machine interface and operational support are used for reflecting the context features, but there are no more specific descriptions for the context. IDAC identifies a set of PIFs that are crucial for relating crew behavior to the NPP context and individual cognitive characteristics. It allows a precise definition in state assessment and causal mechanisms, which can help interpret small differences in the context which could result in visible different behaviors. CFM develops an elaborate PSFs specific to the factors influencing human performance in spaceflight, which describes various aspects of spaceflight context at a very detailed level. In the view of human-technical system-environment interaction, the STC context is dissected based on STC task analysis and literature review. And we confirmed the validity of the PSFs with evidences from STC accidents and incidents, which are collected and compiled from relevant literature and websites report. The various unique working conditions of STC are identified as specific as possible in our study.

*4.3.2 Normalization of definition.* Normalization of definition is used to evaluate that if the PSF taxonomy meets definitional orthogonality and value neutrality. The PSFs that are

The main component	The component categories	PSFs groups	PSFs	
Human	Physical factors	Physical conditions	1. Age 2. Fatigue 3. Physical limitations	
		Memorized information	Memory of recent situation Long-term memory	4. Working memory 5. Knowledge and experience 6. Skill
	Mental state	Cognitive modes and tendencies		7. Attention 8. Alertness 9. Bias
			Emotional arousal Psychological load and feelings	10. Stress 11. Time-constrain load 12. Task load 13. Passive information load 14. Confidence level
		Perception and appraisal		15. Perceived urgency of current situation 16. Perceived familiarity with situation 17. Perceived criticality of current task 18. Perceived complexity of current task
			Intrinsic characteristics	19. Awareness of responsibility 20. Personality type 21. Safety attitude
	Society-related factors	Social attribute	22. Education level 23. Family situation	
		Human-machine interface (HMI)	Control equipment	24. Controller layout 25. Controller availability
	Technical system state		Display equipment	26. Indicator layout 27. Displayer availability
		Technical system	Operating parameter	28. Parameters state 29. System static parameters 30. Change rate of parameter 31. Number of parameter anomalies 32. Number of alarms
Operating phenomena	33. Number of abnormal operating phenomena			
Environment	Natural environment	Meteorological factors	34. Temperature 35. Humidity 36. Air pressure 37. Rainfall	
		Engineering geological characteristics Ground structures	38. Unfavorable geology 39. Distribution of ground structures	
		Underground pipeline	40. Distribution of underground pipeline	
	Working environment	Workplace condition		41. The orderliness of construction site 42. Site layout 43. Adequacy of workspace

**Table I.**  
PSFs taxonomy for  
STC context

(continued)

The main component	The component categories	PSFs groups	PSFs			
Task	Task type	Special environment conditions	44. Illumination intensity			
			45. Oxygen deficiency			
			46. Toxic gas			
			47. Dust and fume			
			48. Noise			
			49. Vibration			
			50. High altitude			
			51. Deep foundation pit			
			52. Extreme temperature			
			53. Teamwork			
			54. Team member's trust			
			55. Team spirit			
			56. Effectiveness of team communication			
			57. Leadership			
			58. Construction schedule			
59. Staffing						
Task	Task attribute	Safety incentive	60. Task assignment			
			61. Availability of equipment			
			62. Material supply level			
			63. Effectiveness of safety incentive			
			Task	Task attribute	Construction scheme and technical measure	64. Effectiveness of construction procedures
						65. Effectiveness of emergency disposal schemes
						66. Supervision and inspection strength
						67. Measurement frequency
						68. Measurement information feedback
						69. Safety training
						70. Onsite safety culture
						71. Construction task
						72. Operational task
						73. Maintenance task
						74. Monitoring task
75. Parallel task						
76. Dependent task						
77. The time of day						
78. Task duration						
79. Available task time						
80. Task complexity						
81. Quantity of hazard						
82. Task novelty						
83. Manual labor strength						
84. Cognitive resource demand						
85. Task consequence						

Table I.

orthogonally defined will omit the possibility of double-counting of influences, which can have spurious influences on quantitative analysis. The value neutrality will ensure that there is an equal opportunity for PSFs to be selected as positive or negative (Kim and Jung, 2003; Groth and Mosleh, 2012). At the same time, using value neutral PIFs will allow

analysts to include shades of gray instead of treating the influence of PSFs as purely positive or negative (Groth and Mosleh, 2012).

In THERP, although the normalization of definition is not emphasized, it proposes three major classes of PSFs (external PSFs, internal PSFs and stressor PSFs) and their subdivisions to distinguish factors that have different influence on human performance. However, the value neutrality is not considered in THERP, for example, “lack of physical exercise,” “high jeopardy risk” and “monotonous, degrading or meaningless work.” CREAM describes the context in terms of a limited number of factors for practical reasons; hence, the proposed CPCs are intended to have a minimum degree of overlap, and a set of value neutral CPCs is used in the method. IDAC provides a precise neutral definition for each PIFs, and ensures that they do not overlap in definition and role in the overall model, since IDAC is developed to be used in computer simulation. CFM includes use of neutral terminology for factor names, as suggested by Groth and Mosleh (2012). Meanwhile, CFM use functional grouping to put together the factors that share similar influence on human performance. In our study, the STC site has gotten an overall description with the guidance of description the “human, technical system, environment and task.” Every important part of the STC site has been considered to avoid overlapping definitions of PSFs as far as possible. But it is hard to reach absolute orthogonality because of the big number of PSFs; this problem is also encountered in THERP, IDAC and CFM as well. On the other side, We make STC PSFs “value neutral” while developing the PSFs, for example, “lack of workspace” could directly impact the performance of workers in many cases, but an ample workspace is rarely discussed. Although we cannot ignore the positive influence, the value of “workspace” can be neutral by changing into “adequacy of workspace” to eliminate the inequality of definition. And all of the four PSF studies use neutral terminology for definition of PSFs.

*4.3.3 Direct influences on the actor.* When evaluating the state of PSFs influencing a behavior, it is necessary to consider what inputs the actor receives and if the actor would perform differently if the inputs were changed (Groth and Mosleh, 2012). The PSFs selected must have a direct influence on the human error occurrences (Kim and Jung, 2003).

THERP does not consider the direct influences of PSFs on human performance. But this attribute has been discussed in CREAM and IDAC. CREAM uses the CPCs to determine the expected effects on performance reliability in quantitative analysis; each CPC has a direct influence on human performance. The PIFs identified in IDAC are mostly the factors that have a direct influence on human performance, also called “frontline” factors. Those factors that have an indirect influence on operators’ response are implicitly modeled by their influences on these frontline factors. In CFM, it makes a distinction between the direct influencing factors and latent influencing factors, and different factors have different level of effects on human behavior. While identifying STC PSFs, it is difficult to distinguish whether a PSF has a direct influence on worker behavior or not in different STC tasks. We do not emphasize the direct influences on the actor in our study. However, if we extend the analysis to include all of the factors, we will collect too much information that is unrelated to the performance of the actor; it will become a difficulty for quantitative analysis.

*4.3.4 Ease of assessment and analysis.* The assessment of PSFs could be difficult due to the illogical classification structure, the number of PSFs and the observability of PSFs. PSF sets should be supplemented with a corresponding set of behaviors and metrics that are visible indicators of invisible PSFs (Groth and Mosleh, 2012), in other words, PSFs sets are assessable in practice (Kim and Jung, 2003).

In THERP, not all of the PSFs are discussed fully or represented in the quantitative models. The method identifies the important PSFs that increase the potential for error of different tasks. CREAM method espouses the use of nine CPCs, and the short list of CPSs simplifies the amount of effort required for an analysis. In order to make the quantitative analysis feasible,

a subset of IDAC PIFs are selected from the wide range of PIFs to capture the major characteristics of human cognitive aspects and individual differences (Chang and Mosleh, 2007b; Coyne, 2009; Li, 2013). It is similar to CFM method. In order to avoid the complexity of analysis caused by the large number of PSFs, the PSFs are extracted from the full set of PSFs with considering those specific situational characteristics. As for STC PSFs, it might be difficult to deal with the PSF set which contains a great number of specific factors. There are 85 PSFs, which means complicated relations exist among those PSFs. It will bring tremendous computing workload besides the complex relations among the factors.

Table II provides an overview of the suitability of the PSF taxonomy with respect to the classification principles discussed above.

Through the evaluation and analysis for existing typical PSFs taxonomies and STC PSFs with those four aspects, we can summarize the performance of STC PSFs as follows:

- (1) Highlighting the context features and definition normalization are bases for PSF taxonomy; most of the existing PSFs studies have considered both of the principles. STC PSF taxonomy meets the requirements of these two principles, as compared to existing PSF-related research studies.
- (2) However, some of the STC PSFs might not have direct influence on worker behavior during different STC tasks. If we model the human behavior with those PSFs that have indirect effects on worker, we will collect too much information that is unrelated to the behavior. We need to avoid collecting information that does not directly influence the behavior we are modeling. Future work should identify the specific subset of PSFs that have direct influence on worker's behavior of different STC task.
- (3) Although STC PSF taxonomy contains the important factors to assess overall task context as comprehensively as it can, a large number of PSFs could bring us the difficulty of assessment and analysis. In the human behavior modeling process where expert judgment is often used to relate context to behavior, it is not practical to consider more than a handful of PSFs (Chang and Mosleh, 2007a). These deficiencies need to be addressed in our future work. It is relatively easy to find that the larger set of THERP PSFs, CREAM CPCs and IDAC PIFs can be reduced through grouping and/or scope reduction, which is a practical solution for the problem.

## 5. Conclusion

This paper introduced a set of PSFs under the context of STC. Based on a "human, system, environment and task" classification frame, we dissect various aspects of the STC context for developing PSFs. The classification frame can support for analyzing the actual construction site conditions and the interaction among human, technical system and environment during

Classification principles	THERP	CREAM	IDAC	CFM	PSF for STC
Highlighting the context features	●	○	●	●	●
Normalization of definition	○	●	●	●	●
Direct influences on the actor	-	○	○	○	○
Ease of assessment and analysis	-	●	○	-	○

**Notes:** "—" The PSFs taxonomy does not consider or does not meet the requirement of the principle; "○" the PSFs taxonomy implicitly consider or partially meet the requirement of the principle; "●" the PSFs taxonomy explicitly consider and meet the requirement of the principle

**Table II.**  
Comparison of  
PSFs taxonomies

construction process. Meanwhile, the combination of mental state factors of IDAC model help to develop the PSFs related to individual cognitive process. And the human-related PSFs are able to explain the individual decision making and cognition mechanisms. With the foundation of the discussion above, a new PSF taxonomy that includes four components and four hierarchies is proposed. Moreover, the reliability of final PSFs was enhanced by analyzing STC accident cases and reviewing the studies related to factors influencing human behaviors of STC and other construction industries. The set of PSFs gives a clearly articulated description of the STC context, and provides evidences for identifying factors leading to human error. Besides the function mentioned above, the new set of PSFs is able to provide a basis for human behavior modeling, and meet the requirements of the computer simulation for personal unsafe behaviors in STC site. The behavior simulation can provide a more realistic and integrated assessment of human error events by directly determining the effect of operator cognitive process. The simulation results could suggest concrete points for the improvement of STC management. We could provide associated safety measures for onsite safety behavior management from the perspectives of individual cognition and human-technical system-environment interaction, for instance, safety training, safety psychology interventions, safety adaptability evaluation and so on.

The development of PSFs is a preliminary step for the research of a simulation-based individual behavior model, which is used to predict human behavior during the STC process. There are still some problems for us. The quantitative analysis in computer simulation puts forward higher request to the definitions of PSFs at a more detailed level, and the difficulty of assessment of PSFs need to be mitigated for quantitative analysis. Hence, the normalization of definition and the quantitative analysis complexity of STC PSFs are required to be improved. In our future work, we need to explore an efficient method to address these two problems. One feasible method is to identify the subset of PSFs specific to the types of crew (e.g. builders, operators, managers and supervisors) and key construction stages (e.g. end-wall reinforcement, portal break, portal airproof and shield tunneling). In other words, we need to classify the STC tasks by different behavior type on the basis of cognitive process analysis of STC tasks. With this method, we can promote a smaller, more specific and more precise set of PSFs, so that the feasibility of PSF quantitative processing would be improved. Meanwhile, we can also try to collapse the hierarchy appropriately and then simplify the PSF taxonomy by systematic aggregation (Groth and Mosleh, 2012). In addition, the PSFs-related data acquisition and processing capabilities can be improved by integrating intelligent data analytics and automated data acquisition technologies (Shi *et al.*, 2017), which might be an effective solution to these problems in future research.

### Notes

1. The accident case originates from a casebook of shield tunnel construction accidents. ISBN: 9787811353693.
2. The accident case originates from a compilation of 14 accidents cases in the website, the case can be found at <http://wenku.baidu.com/view/b9b8ffe35acfa1c7ab00cc96.html>PPT
3. The accident case originates from a news report in website, the case can be found at [www.zlaqw.com/article/1000.html](http://www.zlaqw.com/article/1000.html)

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