Automation in Construction 95 (2018) 118–128

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Proactive behavior-based system for controlling safety risks in urban highway construction megaprojects

Yongkui Li[a], Yi Hu[a,*], Bo Xia[b], Martin Skitmore[b], Heng Li[c]

[a] School of Economics and Management, Tongji University, Shanghai, China.
[b] School of Civil Engineering and The Built Environment, Queensland University of Technology, Brisbane, Australia.
[c] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China.

ARTICLE INFO

Keywords:
Urban highway construction
Megaproject
Safety risk
Behavior-based safety (BBS)
Safety inspection

ABSTRACT

Urban highway construction megaprojects are commonly beset by significant and dynamic safety risks because of their large size, the scattered nature of the works involved, compressed construction schedules, technical difficulties and numerous participants. However, traditional on-site safety inspection cannot fully address all challenges, particularly those with behavior-based safety (BBS) risks. To deal with these challenges, this study describes the novel use of the proactive construction management system (PCMS) with a third-party safety inspection program. The definition, abstraction and implementation processes of the PCMS-aided third-party inspection program are demonstrated and tested through a case study of the Shanghai Central Loop Pudong highway construction project with multi-section sites. Based on a "before and after" comparative study, quantitative and qualitative data are triangulated to evaluate variations in the effectiveness of third-party inspection programs with and without the PCMS aided at the macro, *meso*, and micro levels. Results indicate the usefulness of the novel idea that applies the PCMS as a part of a third-party inspection program to improve BBS risk control on certain risky sites and incorporates its feedback into third-party inspection on all section sites to strengthen the overall safety training, safety inspection, and timely safety risk responses. These results not only provide an increased understanding of the role of PCMS in the safety management of highway megaprojects and the guidelines required for its future application but also serve as a precursor to future research into megaproject safety management.

1. Introduction

Urban highway construction megaprojects are commonly beset with significant and dynamic safety risks because of their large size, the dispersed execution by various contractors, compressed construction schedules and significant technical difficulties, which trigger the need for owners to monitor on-site safety risks in different locations. Such megaprojects involve significantly elevated road construction in which behavior-based safety (BBS) risks are the main cause of fatal accidents. According to a review in the online *National Accident Bulletins* released by the State Administration of Work Safety, 49 major accidents, involving an average of 3.7 deaths, occurred on Chinese highway construction sites between 2010 and 2014. Approximately half of these deaths were due to the unsafe actions of workers, such as falling from a height and being hit with falling objects, because of the absence of appropriate protection measures.

The Shanghai Central Loop (SCL) Pudong project, involving the construction of a 9.44-km elevated road at a cost of CNY11.4 billion, is one of the largest public investments in the city after the Shanghai World Expo site construction. It faced a significant challenge of controlling safety risks on the 16 dispersed section-sites caused by the following factors: First, given the compressed schedule requirement, the megaproject adopted a dispersed concurrent construction method that divided all construction activities into 16 bidding packages for construction and executed them on the 16 separate section-sites, which increased difficulties in decision-making and making timely improvements in risk control at the macro (entire multi-location project) level. Second, the majority of highways in the project were elevated roads with a designed height of 39.3 m, which led to a considerable amount of working-at-height activities, non-standardized processes, and scattered working locations at the micro level, thereby resulting in a significant challenge in BBS risk control during construction processes. Traditionally, managing these risks relies heavily on the on-site safety supervisory monitoring systems of major contractors or owner-

* Corresponding author at: School of Economics and Management, Tongji University, 1239 Siping Road, Shanghai 200092, China.
E-mail address: yi_hu@tongji.edu.cn (Y. Hu).

https://doi.org/10.1016/j.autcon.2018.07.021
Received 22 March 2016; Received in revised form 6 June 2018; Accepted 31 July 2018
0926-5805/

employed consultants. However, the method cannot handle the challenge faced by the megaproject involving dozens of major-section contractors and section supervisors, due to the low efficiency and effectiveness of the overall real-time monitoring, integration and reporting of dispersed safety monitoring tasks at the different section-sites. Thus, a holistic and proactive approach was needed for the owner to integrate macro supervision and micro monitoring across different levels of the megaproject's safety risk control.

The megaproject owner introduced a third-party involvement program integrated with the proactive construction management system (PCMS), which is a proactive behavior-based system, to handle the safety risk control challenge across the macro and micro levels in the case megaproject. This decision was inspired by the successful experience of local metro construction management in initiating and implementing third-party risk assessment programs for several years and the owner's recognition of their inadequacy in monitoring dynamic BBS risks, which was unfamiliar to the owner in terms of the required resources and experience needed.

The PCMS-aided third-party safety inspection program is a new approach. Thus, this study aimed to examine how PCMS can be effectively incorporated into the third-party safety inspection program and investigate the challenges, risks, processes, benefits, and critical components involved to provide a useful reference for the further involvement of third parties in safety supervision practices in similar projects.

2. Literature review

2.1. Supervisory monitoring practices for construction safety risk management

Supervisory monitoring plays a pivotal role in construction-safety risk management. Although construction safety risk identification and assessment have significantly progressed in the past two decades [1,2,3], minimal attention has been paid to the prevention of the various safety risks involved. Cheng et al.'s construction safety risk classification framework indicates that supervisory monitoring is widely accepted as a fundamental approach to controlling most safety risks, such as those related to workers, environment and equipment, project management and schedule pressure [4]. In addition, previous studies have mainly focused on the dominant role of contractors in supervisory monitoring practices, whose effectiveness is mainly constrained by the abilities of main contractors [5].

Using collective protection measures can relieve the burden of contractors and ultimately contribute to improved safety; thus, the development of a multi-party collaborative approach to safety management has attracted increasing interest over the past decade [6,7]. Earlier studies have indicated that providing designers with health and safety training could improve on-site safety risk control, thereby leading to an improvement in safety and on-site accident prevention [6]. An increasing number of studies have revealed the positive impact of inter-organizational collaboration between owners and contractors in improving on-site safety [8,9], but they seldom consider the potential impact of emerging safety technologies (e.g., PCMS) on inter-organizational collaboration.

2.2. Developments in BBS research and proactive BBS systems

BBS research provides a useful means of improving safety performance through the active intervention of a BBS risk management process [10]. The concept was first applied in the manufacturing industry in the 1980s and was later diffused into the construction industry. The increasing number of research studies in the past three decades has indicated the increasing interest in this area; the majority of these studies focused on the identification of the root of unsafe or hazardous behaviors using various measurement instruments for organizations, cultures and climates [3,11,12]. Recent studies in this area have focused on actively responding to BBS risks [13,14,15].

According to the risk management model of socio-technical systems suggested by Rasmussen [16], existing risk response strategies can be grouped into social/organizational and technical responses. Social/organizational responses refer to the research perspective that regards BBS as a form of reinforcement. Correspondingly, several studies have proposed organizational strategies for the implementation of BBS systems, such as purposive training [15], leadership development [17], regulation and rule adjustment [18] and encouragement methods [3]. Although the decisive role of people's behavior has been considerably debated because of its vulnerability to such external factors as climate and culture [19,20], existing empirical studies have shown that BBS can significantly address immediate behavioral risks and prevent potential hazards [21].

Recent technological developments in proximity warning systems have provided an active method of intervening in the safety behavior of individual workers through the combined use of real-time location and data visualization technologies. PCMS, which was proposed by Li et al. [22] to improve the BBS of individual workers, is a form of proactive BBS system. In comparison with existing BBS methods that emphasize psychological reinforcement, PCMS is an automatic behavior-risk warning system that can collect real-time location-based behavioral data from workers for safety supervision and provide real-time warnings when they are exposed to risky situations. In the PCMS, the risk factors that may trigger a worker's unsafe behavior are dynamically integrated with information that concerns the worker's behavior and location to evaluate the present situation and raise audio and vibration warnings according to pre-set rules. PCMS acts as an automatic eye that helps workers strengthen their cognitive abilities in assessing their current location. Moreover, warnings are triggered and continue until the unsafe behavior ends, which cultivates good safety-related habits. PCMS has three functions of hazard detection, safety data recording and analysis, and safety training. The application of PCMS over a nine-week intervention period in Hong Kong resulted in construction safety improvement [23].

PCMS is still an emerging technology and its expensive cost hinders its wide application. Moreover, incorporating this new technology into existing safety supervisory monitoring practices or safety inspection systems, particularly in megaprojects with significant BBS risks, poses a practical, yet theoretical, question to researchers and practitioners in the long run.

3. Research methodology

PCMS was employed in the safety inspection program in Period I (September 2013 to September 2014) of the SCL Pudong project because of the limitations of implementing the third-party safety inspection program in terms of its inadequacy in controlling the workers' BBS risks. Thus, a field trial was used in Period II (December 2014 to April 2015)to develop and implement the PCMS-aided safety inspection program for controlling safety risks at the macro, *meso*, and micro levels. A comparative analysis was conducted at each of the micro (workers), *meso* (section sites) and macro (all 16 section-sites) levels to ascertain the effectiveness of the PCMS-aided safety inspection program. Multiple data collection methods, such as archival documents, field trials, questionnaire surveys, and interviews, were triangulated to improve research reliability and eliminate possible bias in the data sources. Moreover, the opinions of the different participants (e.g., contractors, owners, and workers) involved in the PCMS were obtained to provide an overall depiction of the implementation process for the validation of the case study [24].

In view of the three-stage process mode of the system of innovation (SoI) by Mostafavi et al. [25], this study streamlined the definition, abstraction (design), and implementation processes and activities of the innovation program into three stages (Fig. 1). In the case project, the development and application of the PCMS-aided safety inspection