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

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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.

Keywords: Urban highway construction, megaproject, safety risk, behavior-based safety (BBS), safety inspection.

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 meters, 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-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 (Figure1). In the case project, the development and application of the PCMS-aided safety inspection program involved two cycles of definition, abstraction, and implementation, as shown in Figure 1.

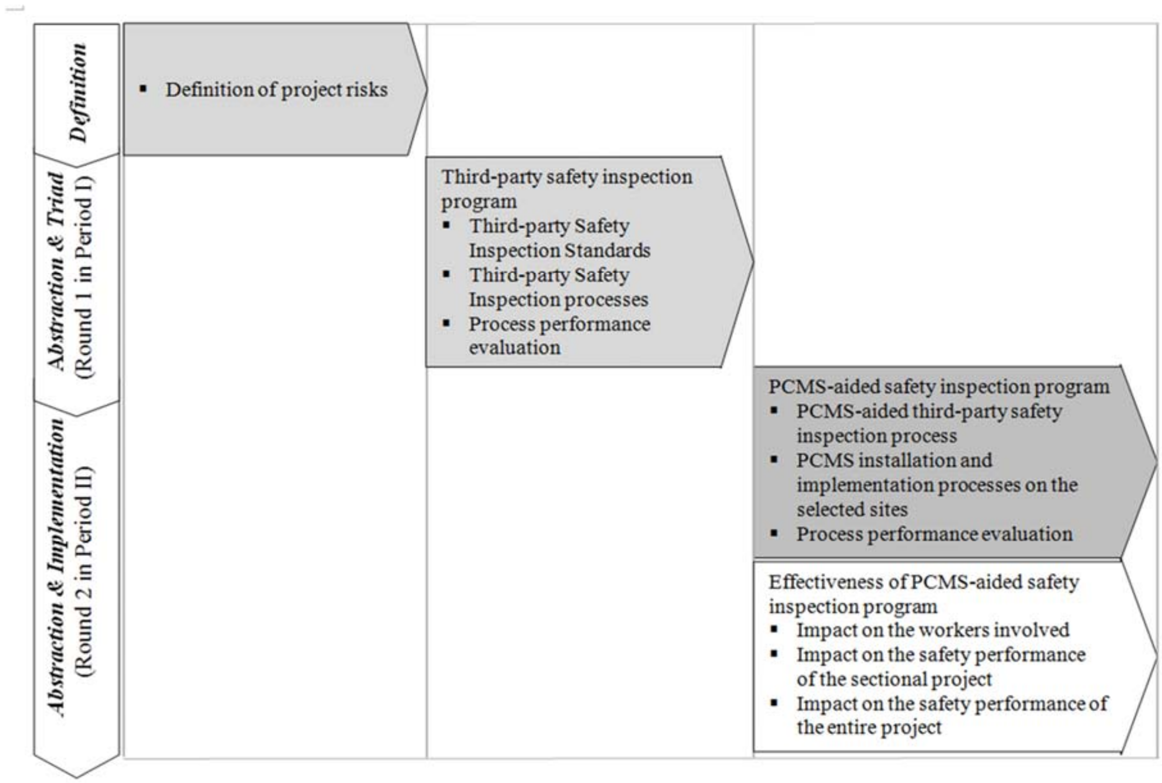

Figure 1.Framework of implementing the PCMS-aided safety inspection program

First, the third-party safety inspection program was developed and trialed on the case project. Next, the PCMS-aided safety inspection program was developed and implemented based on the process performance of the safety inspection program in Period I and the earlier implementation results of the PCMS. Finally, the effectiveness of the improved program was examined in Period II through the three comparative analyses at the macro, meso, and micro levels.

4. Case Background and Safety Risks Identified

SCL is one of the four highways that surround Shanghai City between the inner loop and the S20 outside loop highway. The construction period lasted 29 months from August 2013 to

December 2015. The SCL construction mainly includes two megaprojects the Pudong and the Puxi projects separated by the Huangpu River. This study focused on the SCL Pudong project, which involved a 9.44-km dual 8-lane elevated road with five entrance and exit ramps from the Jungong cross-river tunnel exit (under the Huangpu River) to the Middle Gaoke Road. The project faced a significant challenge of safety risk control caused by the following factors:

(a) Given that the case project is one of the largest public investments in the city after the Shanghai Expo site construction and its construction sites were located in urban areas, the safety management of the case project received significant attention from the government, the public, and nearby communities.

(b) Given that the 29-monthschedule requirement, which is compressed compared with local urban highway construction records, the use of concurrent construction method that divided the entire project into 16 bidding packages and undertook them on 16 separate section-sites led to a significant challenge for the owner in safety risk control at the overall project level.

(c) The elevated road in the case project has a designed height of 39.3 m, breaking the record for local elevated roads. The construction of the highly elevated road inevitably caused BBS risks related to superstructure works during the construction processes, such as falling injuries, falling objects, fire, electric shocks, crane collapse and chemical poisoning.

5. Abstraction and Trial of Third-party Safety Inspection Program

The third-party safety inspection program was first introduced by the owner to establish a centralized on-site safety supervision system that could integrate and monitor the dispersed safety supervision tasks of different construction contractors' safety officers and supervisors on 16 section−sites. The owner invited a consultant from a local university to help with the development of this innovative program in highway construction through a participatory field trial because of the owner's lack of experience in the area.

5.1 Safety Inspection Standards

17 on-site safety inspection items were determined with reference to the national and local safety inspection standards for public projects [26, 27] and the review results of safety risks and causes of accidents combined with those of the review of local site management regulations and owner requirements. These items can be categorized into four safety management factors of (1) major engineering construction safety, (2) general security, (3) emergency management and (4) safety management process (Table2).

Table 2. Third-party safety-inspection risk aspects and items

Aspects	Inspection items
Major engineering construction safety	Municipal utilities protection
	Piling safety
	Earthwork and foundation safety
	Scaffolding safety
	Formwork safety
	Crane and equipment use
	Pre-stressed concrete safety
	Anti-collision guardrail installation
	Pipe jacking safety
General security	On-site security
	Migrant workers' living areas
	Temporary electrical use
	Fire control measures
Emergency management	Flood control measures

Safety management process	Safety training and inspection records
	Special engineering construction plans and execution
	Major danger management plans and execution

5.2Safety Inspection Process

The safety inspection period lasted for approximately 24 months and was divided into three periods: Period I (September 2013 to September 2014), Period II (November 2014 to April 2015) with the incorporation of PCMS, and Period III (May to September 2015) without PCMS. The use of the PCMS was terminated in Period III because most section sites had completed the construction of the main structures, resulting in a significant decrease in working-at-height activities and associated BBS risks. A review of the third-party safety inspection in Period I was conducted in October 2014.The safety inspection group, which comprised a third-party group of certified safety engineers, civil engineers, facilitators and representatives of the section contractors and section construction supervisors, conducted monthly on-site inspections. Figure 2 shows that the third-party on-site inspection process was determined as follows.

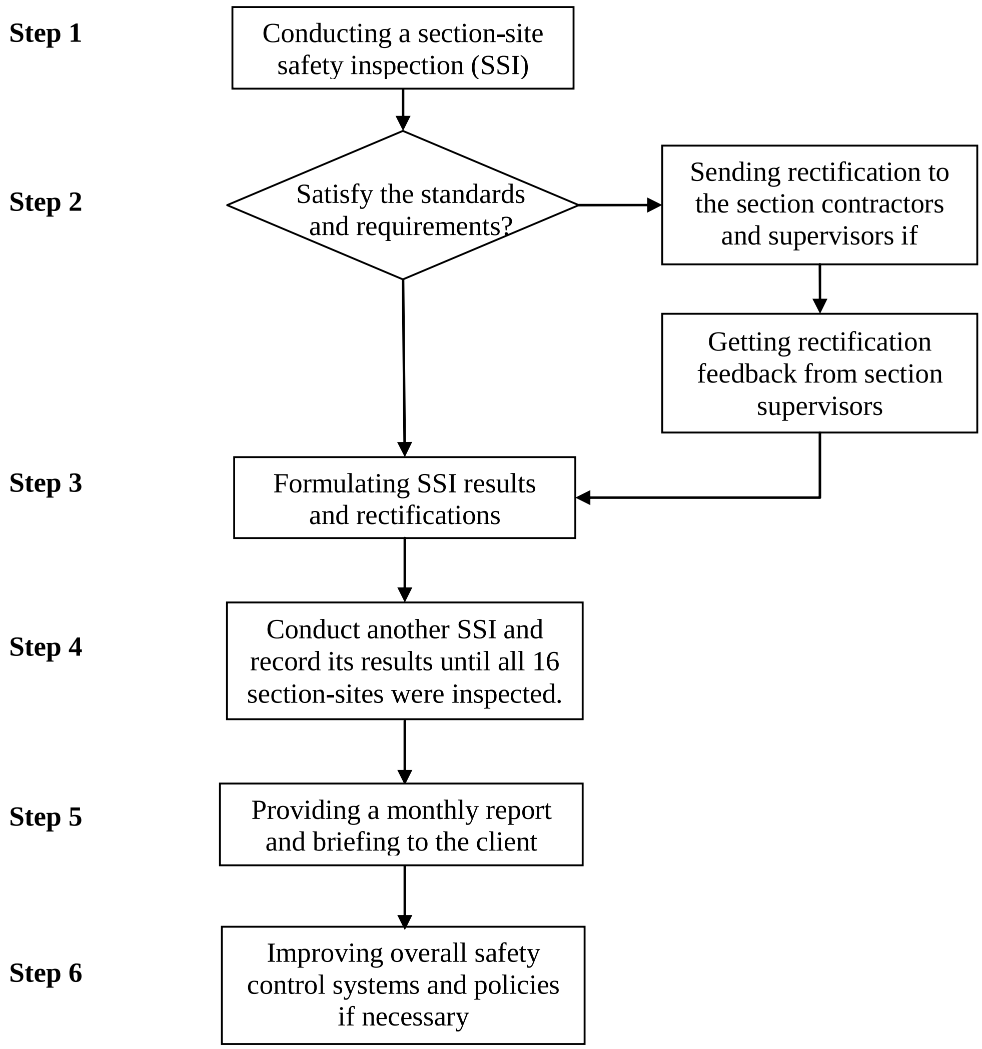

Figure 2. Third-party Safety Inspection Process

Step 1: A site safety inspection (SSI) was conducted on a particular section site in terms of the pre-defined standards. Each inspection visit to a particular section-site at each month was conducted without prior notice and lasting one or two days.

Step 2: Rectification notices were issued as necessary. The inspection group rechecked rectification issues and asked on-site supervisors to solve the issues. Rectification feedback was obtained from section supervisors within a month and rectified safety items rechecked as necessary.

Step 3: The SSI results on the site were recorded. The results included inspection records, photographs, rectification feedback and feedback from section supervisors and contractors.

Step 4: The SSI visit to another section-site was conducted until all 16 section-sites were inspected.

Step 5: A monthly report and briefing were provided for the owner. The report mainly contained a summary of the inspection works, major safety risks and their frequency, rectification progress and recommendations for future work.

Step 6: The overall on-site safety management system and policies were improved where necessary.

5.3 Process Performance

The third−party group in Period I conducted a safety inspection of each section site 51times and identified the 10 most important risks with a total frequency of 1398, which validated the usefulness of the earlier accident reviews and the safety inspection standards. Figure 3 shows the increasing trend of the 10 major safety risks. Six of these risks are related to BBS risks, which comprise “L1-Temporary electricity use,”“L2-Temporary protection for holes and edges,”“L5-Dangerous goods,” “L7-Device management,” “L9-Crane lifting,” and “L10-Unsafe behavior of workers”. According to the feedback from the third−party team, Sections 3, 11, and 13 experienced the most frequent occurrence of the 10 risks.

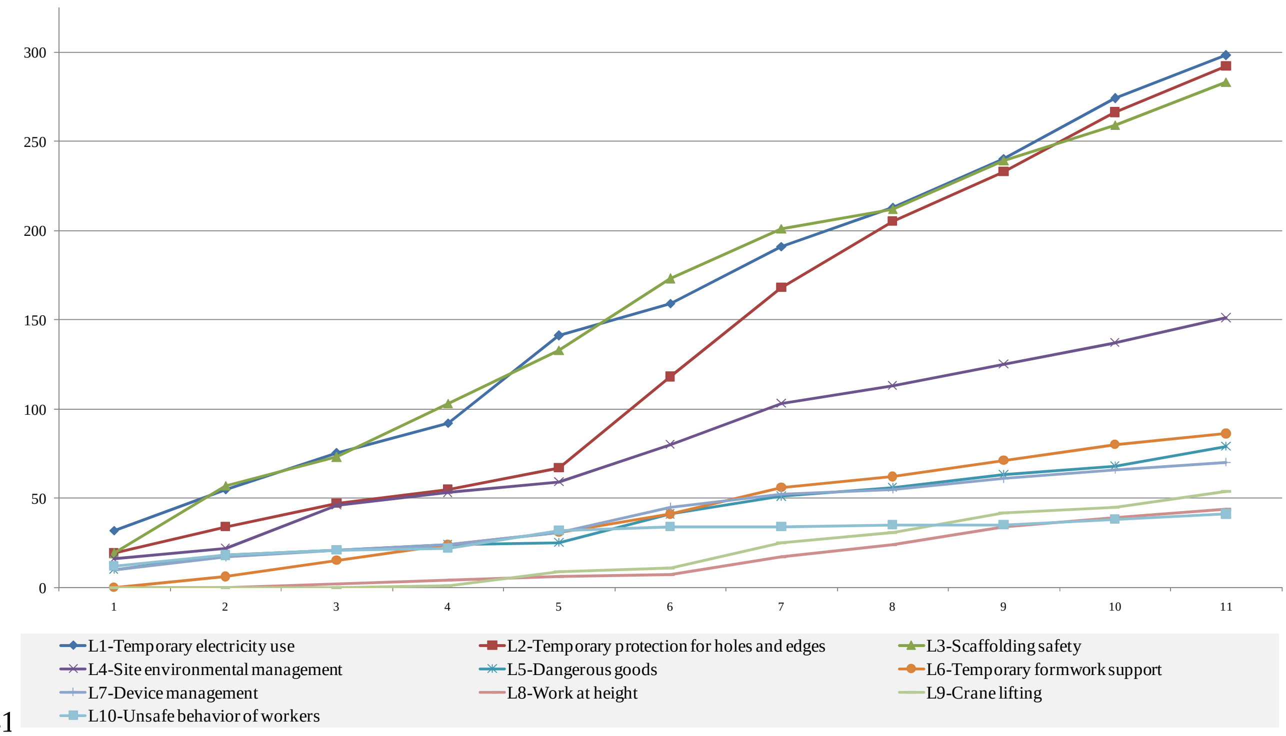

Figure 3. Frequency of the 10 major safety risks during Period I

6. Abstraction and Implementation of PCMS-aided Safety Inspection Program

6.1 Safety Inspection Process

The owner requested the third party to introduce new technologies for monitoring dynamic BBS risks because of the falling injuries in Period I. After evaluating different technological alternatives, PCMS was selected and applied by the third-party team in Period II, which lasted for five months from December 2014 to April 2015. The PCMS was installed onSection3with the support of the PCMS group, which was a newly established group of the third-party inspection team, based on an evaluation of the BBS risks of all 16 sections-sites and the extra budget approved. Figure 4 shows the third-party safety inspection process after the introduction of the PCMS into the project's Section 3.

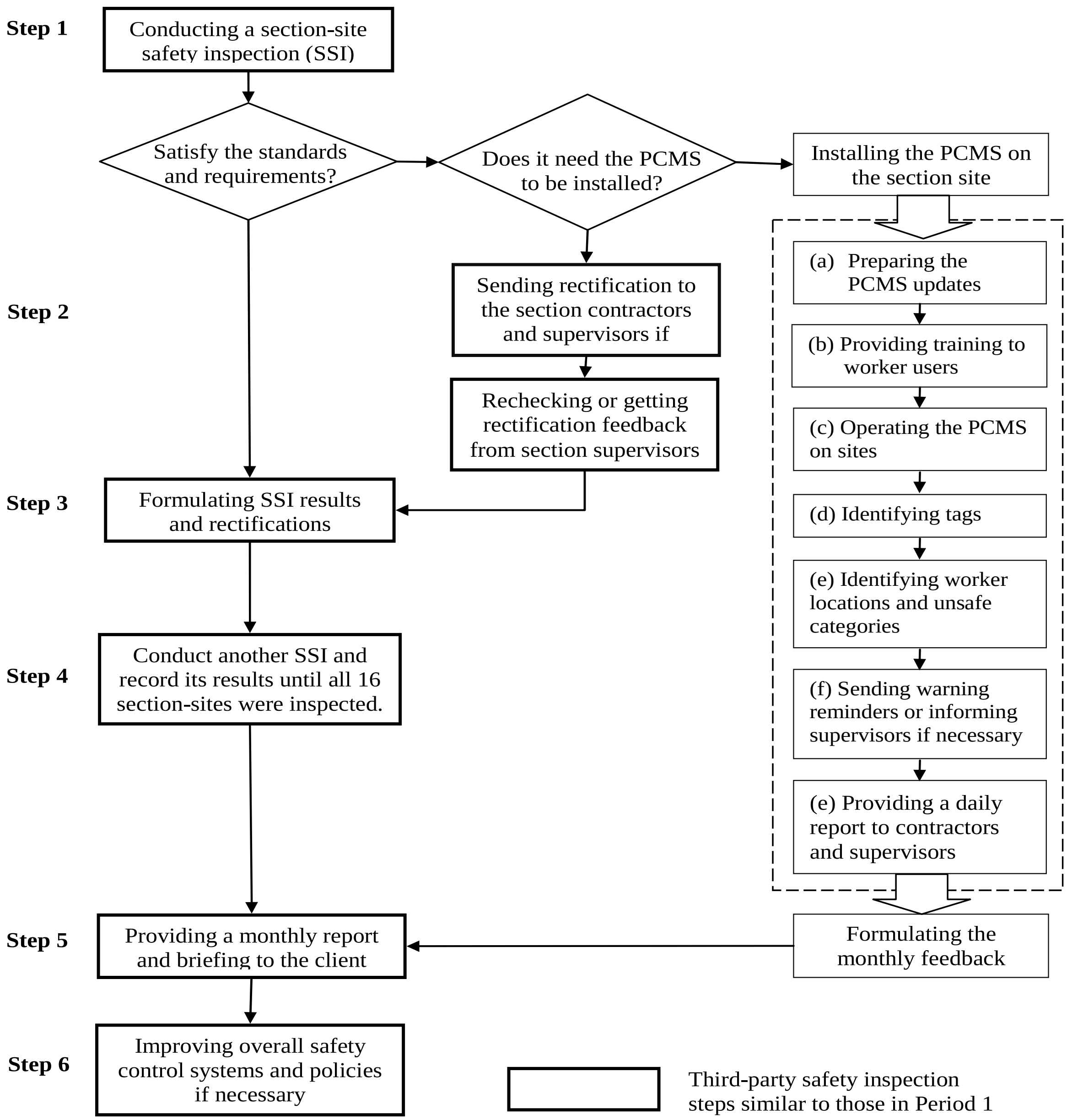

Figure 4. PCMS-aided Third-party Safety Inspection Process

Step 1: The third-party safety inspection group conducted monthly SSIs to all 16 section-sites.

Step 2: PCMS would be installed on certain section sites if significant BBS risks were identified in their SSIs. In the case project, Section 3 site was selected for the installation of

PCMS. After a series of activities (a)-(e) (Figure 4) reported later, a separate group was established as a part of the third-party team in Period II to operate PCMS on the section-site.

Step 3: Rectification feedback regarding the SSIs was sent to the section supervisor and contractors. Section 3 also received a monthly SSI in case the PCMS was installed on the site.

Step 4: The SSI results and rectifications of all 16 section sites were formulated by the third-party safety inspection group by the month end of Period II. The PCMS group carried out similar formulations.

Step 5: A monthly report containing feedback from the third-party safety inspection group and PCMS groups was drafted mainly by the safety inspection group. The report was provided to the owner. The monthly report contained not only a summary of all the inspection works and details of the major safety risks identified (e.g., the frequency of the major risks, rectification progress and recommendations for future work) but also the recorded PCMS warnings and their potential ramifications on other section sites. In addition, the report was sent to the contractors and supervisors of all 16 section sites to help them understand their safety management performance and improve related work.

Step 6: Improvements in the overall on-site safety management system and policies were made if necessary.

6.2 Installation and Implementation Processes on Section 3 Site

After discussions with the case project owner, PCMS was introduced into the SCL project using an on-site PCMS group under the supervision of the safety inspection group in October 2014 to strengthen the real-time control of BBS risks in several construction section sites. This project was the second to use PCMS and the first to utilize it in urban highway construction projects. After several discussions with the owner, PCMS was used in Section 3 of the case project due to the significant BBS risks identified by the inspections. Figure 4 indicates that the PCMS was installed on Section 3 site in terms of the following procedures:

(a) Unsafe behavior rules were determined before developing PCMS updates. Nine unsafe areas related to major BBS risks were initially identified based on the diagnosed BBS risks (accidents) and discussions with the owner and on-site contractors (Table 3). Regarding earlier PCMS implementation experiences, the unsafe behavior rules were arranged as shown in Table 3. In comparison with the earlier PCMSs, the updated PCMS used in the case study specified additional unsafe behavior rules regarding new unsafe areas in terms of urban highway construction characteristics.

Table 3. Unsafe behavior rules of the PCMS

No.	Unsafe area	Unsafe behavior	Risk	Warning
1	Tower crane	Working radius treated as a possible drop area	Being struck by objects	Mind lifting hook
2	Scaffolding	Coverage area	Being struck by objects	Mind falling objects
3	Formwork	Formwork stripping area	Being struck by objects	Mind falling objects
4	Construction machinery	Operating space	Being struck by moving machinery	Warning of machinery

5	Transportation vehicles	<2 m around the vehicle and its routes	Being struck by moving vehicles	Warning of vehicles
6	Holes	Size<0.5m, the hole alone is classified as a dropping area	Falling from height	Falling caution
		Size>0.5m, the hole and 0.5mperiphery are classified as a dropping area	Falling from height	Falling caution
7	Edges	Height of boundaries<2 m, within 0.5 m is treated as a dropping area	Falling from height	Falling caution
		Height of boundaries>2 m, within 1 m is treated as a dropping area	Falling from height	Falling caution
8	Electricity distribution box	Around 0.5 m	Electric shock	Move away from power lines
9	Dangerous goods	Coverage area	Fire etc.	Mind dangerous cargo

(b) Preparation for the PCMS updates was conducted to enhance the section site requirements before operating the PCMS on site. The PCMS in the case project adopted a system design similar to that used in the previous application [[22], which comprised a back server and a real-time location device. First, a virtual construction model was developed, which integrates data of the construction site conditions, permanent structures, temporary facilities and equipment positions, to plot unsafe areas and provide informational support (Figure 5). Key construction activities, such as crane operations and working at height, were simulated based on the output model before the work commenced, which provided workers with the information required to understand the work requirements and risks involved. Third, the anchor locations of the three types of unsafe points, lines, and areas were determined in terms of the virtual construction model and construction process simulation. Fourth, three positioning zones, namely, on the bridge, under the bridge, and along the connecting slope, were designed at different construction phases of the section site in terms of the dynamic nature of the section construction (Figure 6). Finally, location tags and a base station (repeater)were installed at each positioning zone. The location tags were installed on worker helmets for real-time location monitoring (workers), and the repeater was used as a reference for measuring the distance between the tags and the base station. Four base stations were installed in each positioning zone to obtain 2.5-dimensional or 3-dimensional tag location information. Figure7 shows the installation of tags and base stations on the site. More details of the preparation works involved are reported in Luo et al. [28].

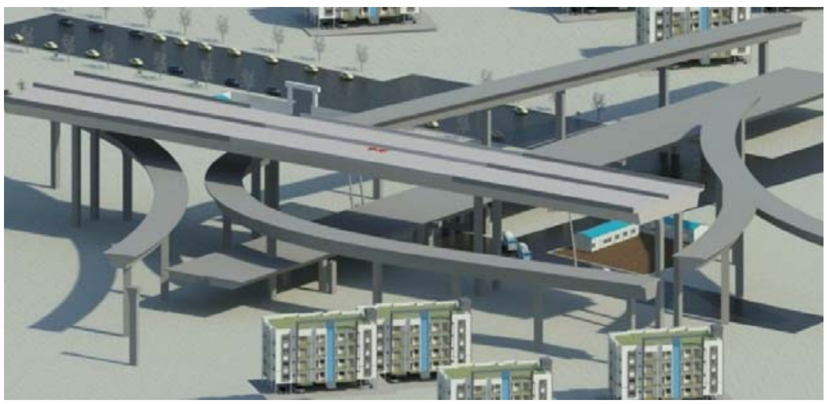

Figure 5. Simulation results of section sites in the PCMS

Figure 6. Configuration of the three positioning zones at different construction phases

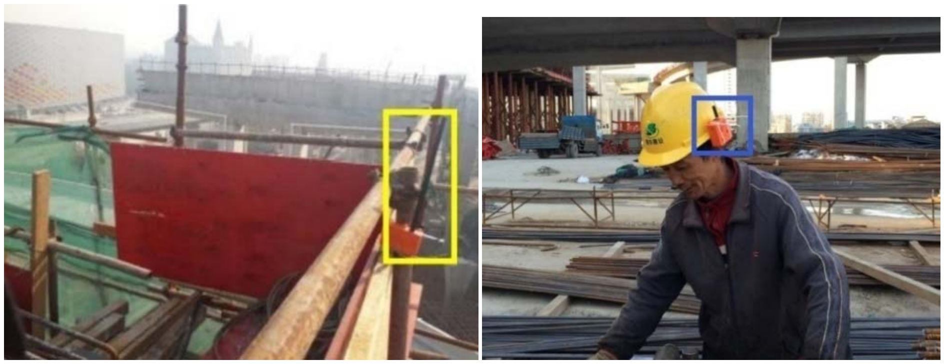

Figure 7. Tags and base stations installed on site

(c) PCMS was operated on site after preparation. In addition, on-site training was provided by the PCMS group to worker users in advance.

(d) PCMS identified the helmet tags through an identifier installed at the site entrance to determine whether workers were authorized to enter the site and had the required safety equipment. This function effectively ensured that workers were wearing safety helmets or shoes.

(e) PCMS collected worker positions dynamically and compared them with the danger zone locations to prevent workers from crossing specific boundaries. Related information was also provided in the computer window to provide supervisors with a global picture (Figure 8). When a worker entered the specific area pre-set in the database, PCMS categorized unsafe sources and assessed their risk levels in terms of pre-defined unsafe behavior rules and worker authorization level with potential hazards.

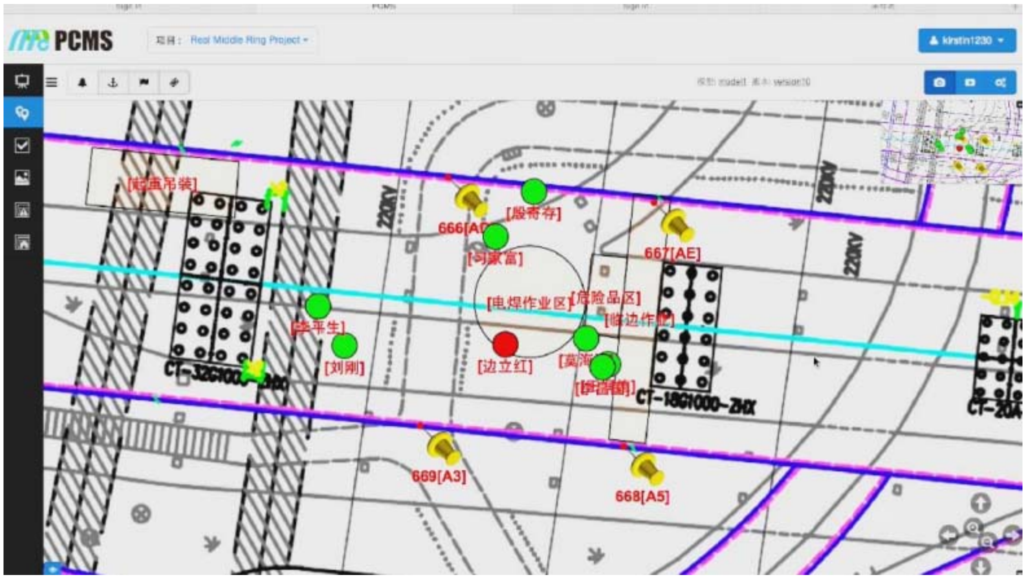

Figure 8. Interface of the PCMS

(f) A warning was given if misbehavior was recorded. Depending on the category of the unsafe areas and the worker authorization, three types of reactions were provided by the system: (1) Unauthorized, in which the system sends a warning of the danger and asks the worker to leave; (2) Authority Level I, which is set for equipment operators, such as the system allowing an authorized worker to drive a tower crane and notifying him of the presence of other workers nearby; and (3) Authority Level II, in which the system provides a warning to a maintenance worker upon entry into a dangerous place and checked for any other sources of danger. Warnings stop with the worker's timely departure from a specific danger zone, otherwise, the warning continues three times while the supervisors check the location of the worker and resolve the problem.

(e) All warnings sent by PCMS were automatically recorded by the system every day and sent to the contractors and on-site supervisor the following day; rectifications were made accordingly.

6.3 Process Performance of the PCMS

The data obtained from the project's Section 3 site included all safety warning information relating to the92 on-site workers from December 2014 to April 2015. The ages of these workers ranged from 23 to 60, with a mean of 42 years. The trial period lasted for 23 working days between December 2014 and April 2015. Two types of workers were involved in the trial, which obtained an average number of daily warnings of 59.6 (for formwork workers) and 71.4 (for rebar workers).Therefore, the rebar workers received more daily warnings than formwork workers. During the trial, 181 sets of daily data for each participant were collected, 136 sets of which were from rebar workers, and 43 sets were from formwork workers.

In view of the dynamic nature of the section construction, the implementation of PCMS was divided into three phases (Table 4).The configuration of on-site PCMS components (mainly base stations) was adjusted to suit the site conditions in each phase. Table 4 shows the in-depth analysis results of the warnings for both types of workers in the trial, which indicates both to have a declining trend over the period. The number of warnings for formwork and rebar workers declined from 88.8 through 76.3 to 28.2, and from 107.4 through 59.2 to 22.0, respectively. This decline is probably because the feedback from the PCMS was sent not only to the workers through real-time warnings but also to on-site contractors and supervisors after each day's test. This system enabled the implementation of more purposive measures in safety training and supervision that not only helped reduce BBS risks for both types of workers involved in the PCMS test but also for similar BBS risks in the same work type in other section sites. Thus, BBS risk control continued to improve across the two worker types although the

PCMS was used by different workers. PCMS testing only included 18 sets of data regarding the warnings for rebar workers per day. Thus, the effectiveness of the PCMS in reducing BBS risks should be investigated further using additional data.

Table4. Statistical results of warning times per day for each type of worker

Phase No.	Type of workers	Type of warnings			All-type hazards	Warning times/day/person
		Type A	Type B	Type C		
1	Formwork workers	933	0	779	1712	88.8
	Rebar workers	4530	181	632	5343	107.4
2	Formwork workers	27	165	0	192	76.3
	Rebar workers	2517	1086	105	3708	59.2
3	Formwork workers	475	183	0	658	28.2
	Rebar workers	85	461	0	546	22.0
	Sum	8567	2076	1516	12161	—

Note: Warnings are classified into three types in terms of safety risk severity relating to the nine unsafe areas. Type A warnings refer to safety risks in crane lifting areas, 'work at-height' areas, 'easy-to-stumble' areas, and edges and holes; Type B warnings refers to aerial work areas and power distribution areas; type C warnings refer to welding areas and the location of dangerous goods.

7. Evaluation of Effectiveness of the PCMS-aided Safety Inspection Program

Three comparative analyses were conducted to evaluate the effectiveness of the PCMS-aided safety inspection program on users, the project section involved and the entire project.

7.1Impact on PCMS users

To ascertain the impact of the PCMS on its users, the opinions were gathered from on-site workers using the PCMS and workers without it for similar work types using a safety climate survey conducted in early 2015. This survey involved Fang et al.'s [29] safety climate statements, with the respondents rating their degree of agreement with each statement on a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree)—one of the most popular scales used in construction safety climate surveys in China [29, 30]. The questionnaire was distributed to Group 1 (using the PCMS) and Group 2 (not using the PCMS) on the Section 3 site. Groups 1 and 2 comprised 14 and 18 workers, respectively. Table 5 shows the profiles of all the members of the two groups. The Table indicates that the members of the two groups are similar in gender, age, education and work experience.

Table 5. Profile of respondents

Respondent profile		Group 1		Group 2	
		Number	Percentage	Number	Percentage
Gender	Male	13	92.9%	17	94.4%
	Female	1	7.1%	1	5.6%
Age (years)	Under 25	—	—	1	5.6%
	25~34	2	14.3%	—	—
	35~44	9	64.3%	3	16.7%
	45~55	2	14.3%	12	66.7%
	Above 55	1	7.1%	2	11.1%
Educational level	Middle school or below	5	35.7%	14	77.8%
	High school or equivalent	8	57.1%	4	22.2%
	Bachelor or above	1	7.1%	—	—
Work experience (years)	1-5	3	21.4%	5	27.8%
	6~10	6	42.9%	3	16.7%
	11~15	4	28.6%	4	22.2%
	16~20	—	—	1	5.6%
	>20	1	7.1%	5	27.8%

The Mann–Whitney test was conducted to determine whether a significant difference in the workers' safety climate perceptions exists between the two groups (H_1). When H_1 is rejected, the alternative hypothesis (H_0) is that the two groups of workers have a similar perception of safety climate. The test results indicate that the two groups of workers have a significantly different perception on the seven measurement items (Table 6) and H_1 is accepted. The findings obtained after further examination of the data in Table6wereas follows. First, the differences in Item 1 maybe due to the use of PCMS, which reduced the working load of traditional on-site supervision and helped workers develop good safety-related working habits in a pro-active way. Second, the differences in Items 2, 3, 4, 5, and 6 indicate that the workers in Group 2 had a greater awareness of BBS risks and could recognize potential deficiencies in on-site safety management better than the workers in Group 1. Third, the improved ratings of Item 7 indicate that the workers in Group 2 had a more objective attitude toward the occurrence of accidents than those in Group 1. These findings reveal the positive effects of the PCMS in the field trials.

Table 6. Group differences in rating the safety-climate measurement items

No.	Item content	Mean of Group 1	Mean of Group 2	Mann-Whitney p
1	Staff are praised for working safely.	4.15	3.22	0.001
2	There is a good preparedness for an emergency here.	3.93	3.33	0.014
3	Sufficient resources are available for health and safety here.	3.92	3.06	0.001
4	I feel involved in the development and review of the health and safety procedures or the conduct of risk assessment.	3.21	2.39	0.022
5	Some jobs here are difficult to do safely.	3.15	3.72	0.027
6	Some health and safety rules or procedures do not reflect how the job is now done.	2.50	3.11	0.027
7	People are just unlucky when they suffer from an accident.	1.79	2.61	0.002

Six semi-structured interviews were further conducted with the management staff of the major contractors involved to analyze the usefulness of the PCMS in influencing the safety behavior of the workers involved. All interviewees were asked to rate the performance of PCMS on a Likert scale ranging from 1(very low) to 9(very high), which is an improved rating system compared with the 10-point rating system commonly used in Chinese studies [31].

Table 7 shows the ratings given by the participants of the four performance indicators of PCMS during its trial period.

Table 7. Ratings of the performance of the PCMS

No.	Assessment Items	Mean ratings
1	Convenience of the PCMS tags	4.2
2	Sensitivity of the PCMS (e.g. receiving signals)	6.0
3	Usefulness of the PCMS warnings	5.2
4	Perceived impact of the PCMS on the workers' BBS	6.7

Table 7 shows that, in addition to assessment item 1, other three items regarding the performance of the PCMS in the trial received mean ratings of above the cutoff value (5), which indicates that PCMS performed well. These subjective ratings are consistent with an earlier objective analysis of a part of the trial data [32]. The results are also consistent with the comments of most interviewees, in that the PCMS is an emerging technology that can help improve the safety behavior of on-site workers and the real-time monitoring of such risky construction activities as working-at-height. Moreover, most interviewees stated that PCMS has a significant potential for application on similar projects. A further question asked, "What improvements, if any, could be made by PCMS to work safety?" Most interviewees responded by commenting on the heavy weight of the tags and the expensive rental fee involved, although they intended to continue supporting the testing and development of the system.

7.2 Impact of PCMS on the Section Project Involved

A *t*-test was further conducted to ascertain whether the adoption of PCMS could reduce BBS risks and had any positive impact on their control in Section 3. Table 8 lists the mean values of the frequency of the major risks identified through safety inspection before and after the use of PCMS in Section 3.The Table indicates that six major BBS risks were reduced by PCMS: “L1-Temporary electricity use,” “L2-Temporary protection for holes and edges,” “L5-Dangerous goods,” “L7-Device management,” “L9-Crane lifting,” and “L10-Unsafe behavior of workers.”These results are consistent with the earlier analysis of the three types of warnings received by the workers during the PCMS application period. The t-values regarding the L2, L5, and L7 risks were significant (at the 5% level), which indicates the usefulness of PCMS in controlling these risks. Several interviewees from the major contractors stated that on-site safety supervisors and managers should adopt more purposeful improvement measures, such as improving the protection of edges and holes and the management of dangerous goods and welding devices in terms of the PCMS feedback to mitigate risks regarding the unsafe behaviors of workers.

Table 8. Comparative analyses of major risks identified before and after the use of PCMS

Top 10 Major risks	Section 3			Overall project		
	Mean monthly risk frequency in Period I(N=11)	Mean monthly risk frequency in Period II(N=4)	t value	Mean monthly risk frequency in Period I(N=11)	Mean monthly risk frequency in Period II(N=4)	t value
L1-Temporary electricity use	3.18	2.75	3.78	27.09	21.75	0.16
L2-Temporary protection for holes and edges	3.36	1.25	5.21[a]	26.55	17.00	4.21
L3-Scaffolding safety	2.55	0.50	3.25	25.73	5.00	4.69
L4-Site environmental management	1.73	0.75	0.07	13.73	6.50	3.92
L5-Dangerous goods	0.91	0	6.16[a]	7.18	3.00	0.14

L6-Temporary formwork support	0	0	—	7.82	2.00	0.66
L7-Device management	0.82	0	10.57 [b]	6.36	2.00	1.57
L8-Work at height	0	0	—	4.00	3.75	0.48
L9-Crane lifting	0.55	0.25	1.81	4.91	2.00	7.32 [a]
L10-Unsafe behavior of workers	0.27	0	1.71	3.45	0.00	6.61 [a]

Notes:

1. The period either between January and February 2014 or between February and March 2015 is regarded as a month because there is the Spring Festival holiday of about one-month for construction workers in China.
2. “a” means “<0.5”; the “b” means “<0.01”.

7.3 Impact of PCMS on the Entire Project

A comparative analysis was conducted using the *t*-test to examine whether the use of the PCMS has any impact on controlling the overall safety risks of the case project. Table 8 shows that the control of the six major BBS risks of workers (i.e., L1, L2, L5, L7, L9 and L10) improved similarly to those in the project’s Section3, which may indicate the positive impact of PCMS on the BBS risk control of the entire project. The *t*-values regarding the six BBS risks are not as significant as those for L9 and L10 risks. However, improvements in the control of the six BBS risks could be easily observed.

Three government officials responsible for supervising the case project were also invited to offer their opinions of the entire third-party involvement program. They strengthened the view that the combination of PCMS and third-party safety inspection is a potential alternative for owners in controlling safety risks and that the third party played an essential role not only in undertaking on-site safety inspection but also in implementing the PCMS. They also suggested that the incorporation of PCMS into the existing safety control system required more collaboration between the third party, major contractors and on-site supervisors, which can help further improve BBS risk control.

8. Conclusions

The complexity and diversity of hazards on highway construction sites have increased significantly due to the rapid emergence of highway megaprojects worldwide. These challenges increased the need to recognize the current rapid development of emerging technologies (e.g., cloud computing, building information modeling, and big data) in safety management, develop the novel use of these technologies, and incorporate them into existing safety risk control systems on highway construction sites, particularly those concerning BBS. However, this issue has seldom been underestimated in previous research, which mainly focuses on the development and testing of emerging technologies, and it seldom considers means of better incorporating these technologies into existing safety management systems. In response, the present study proposes an innovative solution through a third-party involvement program, which consists of the PCMS and third party safety inspections. In addition, it pioneers in the effort of bridging the theoretical gap between the use of emerging proactive BBS technologies and inter-organizational safety collaboration, which paves the way for future research in this area. This solution can not only help owners maintain the overall control of safety risks and improve the integrity of safety data at the macro/meso level, but can also help reduce BBS risks in hazardous locations at the micro level. Moreover, the timely feedback from the trial use of

PCMS on selected section sites can be leveraged to achieve purposeful safety training and monitoring measures on all megaproject section sites.

Based on the before and after comparative analyses, the success of the third-party safety inspection may be attributed to the combined use of PCMS on selected section sites and the overall safety inspections of all section sites through an improved third-party involvement program. The framework for designing and implementing such an innovative third-party inspection program was formulated into two SoI cycles, each of which involves definition, abstraction, and implementation steps. The improved safety inspection process with PCMS not only improved worker safety performance and the efficiency of BBS risk reduction on selected section sites but also contributed to the overall BBS risk control on all 16 section sites.

This study provided further evidences of the usefulness of PCMS in improving the safety awareness of workers and safe behaviors at work through a safety climate survey. The study has two limitations. Several technological weaknesses in PCMS were encountered in the field trial, such as limited accuracy, occasionally low reaction, high cost, limited visibility, and a small number of trial participants involved because of budget constraints. Further development and trials are needed for the technological advancement and continuous improvement of the proposed solution in the future. The other limitation of PCMS is the limited interaction between the safety supervisors or safety officers and the workers, who can detect only location-based BBS risks at this stage. Further work is needed to identify and intervene in the case of BBS risks that are not related to location.

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