Construction safety improvement framework for mass rapid transit projects

Construction Innovation

189

Received 17 June 2024
Revised 30 December 2024
24 March 2025
Accepted 14 April 2025

Md Asrul Nasid Masrom
Department of Construction Management, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Malaysia

Melissa Chan
Institute for Sustainable Industries and Liveable Cities (ISILC), Victoria University, Melbourne, Australia

Chukwuka Christian Ohueri
Department of Construction Project Management, School of Housing, Building and Planning, Universiti Sains Malaysia, Penang, Malaysia, and

Norakmal Hakim Mohd Ramlee and Roshartini Omar
Department of Construction Management, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Malaysia

Abstract

Purpose – Construction sites are among the most hazardous working environments globally, with over 108,000 fatal accidents recorded annually. Contractors' significant role in implementing safety in construction sites has been emphasized. However, a contractor-driven safety framework that addresses the multifaceted safety challenges of complex projects like mass rapid transit (MRT) is lacking, undermining contractors' potential to ensure the safety of construction workers. This study aims to develop the construction safety improvement framework (CSIF) to enable contractors to effectively address emerging challenges in construction safety management.

Design/methodology/approach – A case study of an ongoing MRT construction project in Malaysia was used. Data collection included in-depth interviews and focus group discussion with contractors, engineers, and safety managers in MRT projects. Data was analyzed via thematic content analysis, to inform the development of CSIF.

Findings – The findings illustrate CSIF components, which encompass five pivotal safety improvement measures: gamified training, mental health support, technological advancements, environmental health, and emergency preparedness.

Originality/value – This paper's originality stems from the development of the CSIF, which introduces a comprehensive and forward-thinking approach to improving construction safety, going beyond conventional methods. By incorporating recent advancements, this research makes a unique contribution to the theoretical foundation of construction safety and provides valuable insights into safety practices designed for complex construction projects.

Keywords Accidents, Case study, Construction, Performance, Qualitative study, Safety management

Paper type Research paper

Construction Innovation
Vol. 25 No. 7, 2025
pp. 189-212
Emerald Publishing Limited
1471-4175
DOI 10.1108/CI-06-2024-0175

1. Introduction

The construction industry is a dynamic driver of a country's economic growth through infrastructural development, provision of employment and revenue generation (Awolusi and Marks, 2017). Unfortunately, construction work is one of the most dangerous occupations, with alarming rates of occupational injuries, illnesses and fatalities compared to other industrial jobs (Khalid *et al.*, 2021). According to the International Labor Organization (ILO) report, globally, approximately 108,000 workers lose their lives in construction sites yearly due to accidents, and many others suffer from occupational diseases arising from environmental pollution and past exposure to dangerous substances. In developed countries like the USA, Occupational Safety and Health Administration (OSHA) reported about 5,486 fatal work injuries in 2022, with construction accounting for a significant portion. In developing countries like Malaysia, the Department of Occupational Safety and Health (DOSH) reported 159 construction accidents, including 45 fatalities in 2023. Despite the projected investment of over MYR46bn, the mass rapid transit (MRT) construction project in Malaysia has experienced eight fatal accidents, seven cases of permanent disability and 19 instances of temporary disability within the past four years [Juhari and Arifin, 2020; Department of Occupational Safety and Health (DOSH), 2023].

The reoccurring construction-related accidents have several consequences, such as physical and psychological effects on accident survival, loss of lives and trauma to the family members (Versteeg *et al.*, 2019); direct costs, including equipment damage, treatment of injuries and interruption of workers' income, which disrupt families' livelihood (Ebekozien *et al.*, 2023). Furthermore, Hislop (1999) hammered on indirect costs such as delays, increases in insurance and workers' compensation premiums, legal fees, etc. According to OSHA (2022), the "Fatal Four," which includes falls, struck-by incidents, electrocutions, and caught-in/between accidents, are the leading causes of accident fatality in construction sites. Thus, established health and safety organizations are making significant efforts to ensure safety in construction sites. For instance, OSHA organizes initiatives like the National Safety Stand-Down to Prevent Falls in Construction, raising awareness and educating employers and workers about fall hazards [Occupational Safety and Health Administration (OSHA), 2022]. Similarly, the Health and Safety Executive (HSE) in the UK implements regulations to improve safety standards, focusing on risk assessments, safety training, and enforcement of safety laws [Health and Safety Executive (HSE), 2021]. In Malaysia, DOSH promotes safe working environments by conducting site inspections and implementing regulatory interventions through the Construction Safety Division to prevent accidents on construction sites [Department of Occupational Safety and Health (DOSH), 2024].

While these efforts have contributed in reducing the number of fatalities in construction sites, issues of unreported death mask the true extent of construction accidents. Moreover, accidents persist in the construction industry, evident in ILO (2022) report that the global construction accident fatality rate remains at approximately four per 100,000 construction workers. Furthermore, Tan *et al.* (2022) cited a fatality rate of 6.3 per 100,000 construction workers in Malaysia's construction industry, which is high compared to other industries. While it is compounded by several critical factors and requires a collective effort, the construction industry's safety challenges are predominantly rooted in contractor oversight and negligence [Hislop, 1999; Department of Occupational Safety and Health (DOSH), 2023; Hadi *et al.*, 2024]. This negligence is attributed to contractors' implementation of ineffective safety measures (Ahmed and Hoque, 2018; Giri *et al.*, 2023). These issues exemplify the troubling trend of subpar subcontractor management, the absence of comprehensive inspection and test plans and a noticeable dearth of fundamental safety training (Juhari and Arifin, 2020; Harahap *et al.*, 2024; Buniya *et al.*, 2024). This highlights the need for a well-established strategic safety framework for contractors to effectively incorporate safety measures in construction sites.

Although contractors' role in construction safety and health has been examined, existing studies focus on various aspects due to the fragmented nature of the construction sector. For instance, Teo and Feng (2011) investigated the financial losses incurred by building contractors in Singapore due to construction accidents. Smallwood (2017) explored the impact of third parties in implementing contractors' safety measures on construction sites. Manu *et al.* (2013) evaluated contractors' health and safety practices across South Asian countries, including Malaysia. These studies provide background knowledge on safety practices but did not specifically focus on framework development. Regarding construction safety framework, Teo *et al.* (2016) developed a conceptual framework for a BIM-based site safety practices. Nnaji *et al.* (2018) developed a more robust theoretical framework that uses safety technologies to reduce construction accidents. Similarly, Mahmoud *et al.* (2022) developed a self-regulatory framework to enhance safety performance at the construction stage. Recently, Jain *et al.* (2024) developed a machine-learning-based framework specifically for contractor selection and order allocation in public construction projects considering sustainability, risk, and safety.

However, prevailing safety frameworks are often generic, lacking the specificity needed to address contractor challenges in complex projects. Furthermore, most of the established frameworks focus on isolated safety aspects rather than comprehensive solutions. For example, aspects like mental support and advanced training (Frimpong *et al.*, 2025), environmental health (Zabidi *et al.*, 2024), and emerging technologies (Zoleykani *et al.*, 2024; Mohy *et al.*, 2024) have been ascertained to effectively prevent accidents in construction sites. However, these components are studied in isolation, and how they can be integrated into a unified construction safety framework to enable contractors to effectively reduce accidents in complex construction projects is uncertain. As a result, there remains a lack of a contractor-driven safety framework that addresses the multifaceted safety challenges of complex projects like MRT, undermining contractors' potential to ensure the safety of construction workers (Sankar and Anandh, 2024; Hossain *et al.*, 2025). This leaves critical gap in contractor-driven safety management, worker well-being, and risk mitigation in MRT construction projects. This is where the novelty of this current study lies, in filling the critical gap, by developing construction safety improvement framework (CSIF) specifically tailored for MRT projects.

The futuristic CSIF will enable contractors to effectively address emerging challenges in construction safety management, inherent to large-scale infrastructure construction. Safety is a philosophy that identifies and eliminates job site hazards throughout the lifecycle of a project, which is far from craftsmen wearing headsets on construction sites. Hence, it is paramount to establish and enforce robust and contemporary construction safety measures to minimize accidents, ensure the timely completion of projects, and improve contractors' performances and client satisfaction (ILO, 2022; Smallwood, 2017). The framework emphasizes proactive measures and represents a significant advancement over traditional reactive safety protocols. To achieve the overarching aim of this research, the following research objectives (ROs) are outlined:

RO1. Identify the critical construction safety improvement measures.

RO2. Develop the construction safety improvement framework.

RO3. Validate the developed construction safety improvement framework.

The CSIF is grounded in empirical evidence gathered from multiple case studies and data triangulated via a focus group discussion (FGD), providing a robust foundation for practical implementation. Also, CSIF development is grounded on the Swiss cheese model – safety concept for understanding and managing complex systems and their associated risks (Othman *et al.*, 2018 Shabani *et al.*, 2024). This study not only contributes to academic discourse but also offers a practical tool for policymakers, project managers and safety practitioners to enhance safety performance, reduce workplace incidents and improve overall project outcomes in the MRT construction sector.

2. Literature review

2.1 Contractors' role in construction safety improvement

Construction site safety remains a critical concern globally, with significant implications for workers' health and economic costs. According to the Bureau of Labor Statistics' Census of Fatal Occupational Injuries (2023), the US construction industry experienced 1,075 fatalities, marking the highest number since 2011. According to Manzo (2017), fatalities in the US construction industry result in approximately US$5bn in annual economic losses, including lost productivity, health-care expenses, and lost family income, while also causing significant social impacts such as reduced quality of life. In the UK, 138 work-related fatalities were reported between 2023 and 2024, with the construction sector accounting for 51 deaths. Consequently, this costs the UK construction sector approximately £1.29bn annually in medical treatment, compensation, and welfare support for injured workers [Health and Safety Executive (HSE), 2024a, 2024b]. In Malaysia, the construction sector records the highest occupational fatalities compared to other sectors (Zermane *et al.*, 2020). According to DOSH, of 150 workplace fatalities, 37% occurred in construction, while 28% occurred in manufacturing (Ayob *et al.*, 2018). Major projects in Malaysia, such as the MRT, have also seen rising accident rates, with eight fatal incidents and numerous temporary and permanent disabilities reported in 2023, despite a projected investment of over MYR46bn [Juhari and Arifin, 2020; Department of Occupational Safety and Health (DOSH), 2023].

Preventing accidents throughout all stages of construction projects requires proactive safety measures and protocols that adhere to established regulations and standards (Mohandes *et al.*, 2023). Construction safety is among the fundamental measures of contractors' performance. Karakhan *et al.* (2018) recommend that the first approach to ensuring safety in construction sites is to evaluate the safety maturity of construction contractors before awarding the contract to ensure safety, quality and completion of the project within the scheduled time and available resources. The contractors' safety maturity is reflected in the clarity and alignment of their safety policies with industry standards and regulations (Duryan *et al.*, 2020). The contractors' construction safety research and practices are grounded on seminal literature and accident causation models, providing insights into key challenges and opportunities for improvement. Foundational studies like Hinze (1997) provided early insights on the role of contractors in enforcing effective communication of construction safety measures to enhance safety and health practices. Tam *et al.* (2004) extended this perspective by identifying deficiencies in contractor-led safety management, highlighting that issues such as inadequate training and risk assessments undermine overall site safety performance.

This is further complemented by Holt's (2008) assertion that poor contractors' safety management strategies, including low technology adoption and inadequate incentives to motivate workers, are key barriers to effective safety practices on construction sites. In addition, Manu *et al.* (2013) emphasized the need for main contractors to collaborate with subcontractors and site supervisors to evaluate and address environmental safety challenges. Building upon the trajectory of the foundational studies, recent researchers have advanced construction safety literature, integrating emerging technologies to drive contractors' safety practices. Jahanshahi *et al.* (2017) suggested the use of emerging technologies like swarm robots for patrolling the construction sites to identify leaks, unstable excavations and other potential risks faster than human inspections. Also, the use of quantum computing has been proposed by Bova *et al.* (2021) as an effective approach that has the potential of providing contractors with real-time sensor data to predict potential hazards. Similarly, BIM, computer vision, deep learning, and extended reality are notable technologies that contractors can harness to ensure a safer working environment for construction workers (Zoleykani *et al.*, 2024; Mohy *et al.*, 2024).

Osei-Asibey *et al.* (2021) recognized the potential of the emerging technologies but highlighted concerns over their lack of seamless integration for effective construction safety communication. Moreover, Duc (2024) argued that contractors rarely harness emerging technologies for emergency preparedness, despite their potential to reduce fatal and nonfatal construction accidents. Effective implementation of emerging technologies in construction safety practices requires careful consideration of costs, contractor expertise, and workers' training (Okpala *et al.*, 2020). Considering these factors at the initial stage of the construction project is vital for contractors to establish a strong safety-focused approach. Furthermore, achieving successful safety implementation on-site requires an adequate leadership commitment to safety by the contractors (Indrayana *et al.*, 2023). However, 70% of the accidents on construction sites result from contractors' negligence and noncompliance with established safety regulations (Zailani *et al.*, 2023; Department of Occupational Safety and Health (DOSH), 2023]. This negligence has not only led to tragic fatalities but has also left families grappling with the aftermath of these incidents, often with little or no compensation, thereby casting a dark shadow on the construction industry and the livelihoods of those who ventured into it. Therefore, a robust safety framework that is deeply rooted in accident causation models must be adopted by contractors to ensure a systematic approach to integrating safety measures into the project planning and execution.

Among the prominent and enduring accident prevention theories is the Heinrich accident pyramid, which suggests that reducing minor incidents will proportionally decrease severe accidents (Heinrich, 1931). However, the theory oversimplifies the complexity of modern construction risks by assuming a linear relationship between incident severity and frequency, which does not fully capture the complexities of large-scale projects like MRT construction. By contrast, the reasons theory, often referred to as the Swiss cheese model, provides a more realistic view of accidents in complex systems. The reasons (1990) theory explains that accidents happen when multiple safety barriers fail at the same time due to hidden weaknesses (latent conditions) and human errors (active failures). This approach aligns with the realities of complex construction projects, where contractors must navigate interdependent safety barriers during design, construction, and supervision while conducting training and integrating technology to minimize construction site accidents. The Swiss cheese model is superior as it accounts for systemic vulnerabilities, regulatory gaps and human factors, making it an ideal foundation for a robust contractor safety framework for complex projects like MRT.

2.2 Existing safety frameworks, limitations and contemporary approaches

The role of contractors in minimizing construction accidents has been emphasized (Teo and Feng, 2011; Ali and Omran, 2016). As a result, various construction safety frameworks have been established to enable contractors to effectively improve overall project safety. For instance, Ng *et al.* (2005) developed a framework for evaluating the safety performance of construction contractors. While the study can only be applied to assess performance rather than improving contractors' performance, it provides a concrete background to further research in the domain of construction safety. Subsequent studies such as Teo *et al.* (2016) developed a theoretical framework of the proposed BIM safety system to facilitate the efforts to enhance safety performance in construction sites. Nnaji *et al.*'s (2018) theoretical framework provided a concrete foundation for contractors' to improve safety in construction sites. Mahmoud *et al.* (2022) developed a self-regulatory framework to enhance safety performance at the construction stage. Hussain *et al.* (2023) proposed a conceptual framework for safety training for migrant construction workers using virtual reality techniques. In a more recent study, Jain et al. (2024) developed a machine-learning-based framework specifically for contractor selection and order allocation in public construction projects, considering sustainability, risk, and safety.

However, the existing frameworks narrowly focus on isolated safety aspects rather than comprehensive solutions, hindering contractors from tackling the multifaceted safety challenges in complex construction projects. For example, aspects like mental support and advanced training (Frimpong *et al.*, 2025), environmental health (Zabidi *et al.*, 2024), and emerging technologies (Zoleykani *et al.*, 2024; Mohy *et al.*, 2024) have been ascertained to effectively prevent accidents at construction sites. However, these components are studied in isolation, and how the can be integrated into a unified construction safety framework to enable contractors to effectively reduce accidents in complex construction projects is uncertain. As a result, there remains a lack of a contractor-driven safety framework that addresses the multifaceted safety challenges of complex projects, undermining contractors' potential to ensure the safety of construction workers (Sankar and Anandh, 2024; Hossain *et al.*, 2025). Moreover, Noorliza and Isha (2023) have stressed the lack of contractors' safety protocols that are precisely customized for the unique context of complex projects like MRT construction. This highlights a significant gap in contractor-driven safety management, worker well-being and risk mitigation in complex projects like MRT construction.

To address the knowledge gap, it is necessary to strictly consider the complexity and heterogenous nature of construction projects such as the involvement of numerous stakeholders, intricate logistics and multifaceted project phases. This is to ensure the establishment of a clear pathway for contractors to effectively implement safety measures, thereby averting accidents on construction sites (Chen *et al.*, 2021). This requires incorporating contemporary safety and environmental health measures, technological advancements, workers' training and mental well-being, contractors' competence and emergency responses to minimize accidents in evolving construction practices beyond the state of the art. Hence, this study reviews fragmented studies on construction safety to identify the contemporary safety measures that can enable contractors to improve safety practices during the construction phase of building projects. Table 1 shows contemporary safety measures for contractors to improve safety in construction sites.

Table 1. Construction safety measures for contractors

Sources	Gamified training	Mental health support	Technological advancements	Environmental health	Emergency preparedness
Rivera *et al.* (2024)	✓				
Tohlob and Morsi (2024)				✓	
Guimarães *et al.*, 2023)	✓				
Zhang *et al.* (2024)		✓			
Bova *et al.* (2021)			✓		✓
Jahanshahi *et al.* (2017)			✓		✓
Bansal and Bhattacharya (2024)		✓			
Zaręba *et al.* (2021)				✓	

Source(s): Authors' own work (2025)

The safety measures were retrieved from numerous safety literature sources and remain fragmented, with no study attempting to integrate them together to form a robust framework of safety measures for construction contractors. Besides, a detailed discussion of the sub-measures that constitute each primary safety measure remains lacking in existing studies, justifying the need for more in-depth investigation. Therefore, this study aims to develop the CSIF to enable contractors' management to address emerging challenges in construction safety management effectively. The methodology adopted to actualize the research aim is discussed in the subsequent section.

3. Research methodology

A qualitative research method was adopted to actualize the aim of this research. As viewed by Islam and Aldaihani (2022), qualitative research is a method that focuses on understanding and interpreting the meaning and experiences of individuals or groups within their natural context, providing in-depth insights into complex phenomena. The methodology adopted in this study shown in Figure 1 is adapted from Creswell's (1998) qualitative research approach and adjusted to suit the scope of this current study. The interview questions were guided by the six generic construction safety measures for contractors, identified via literature review. As part of the reliability and validity test proposed by Masrom *et al.* (2024), the developed interview questions were validated by two participants from industry and academia in a pilot interview. The questions were

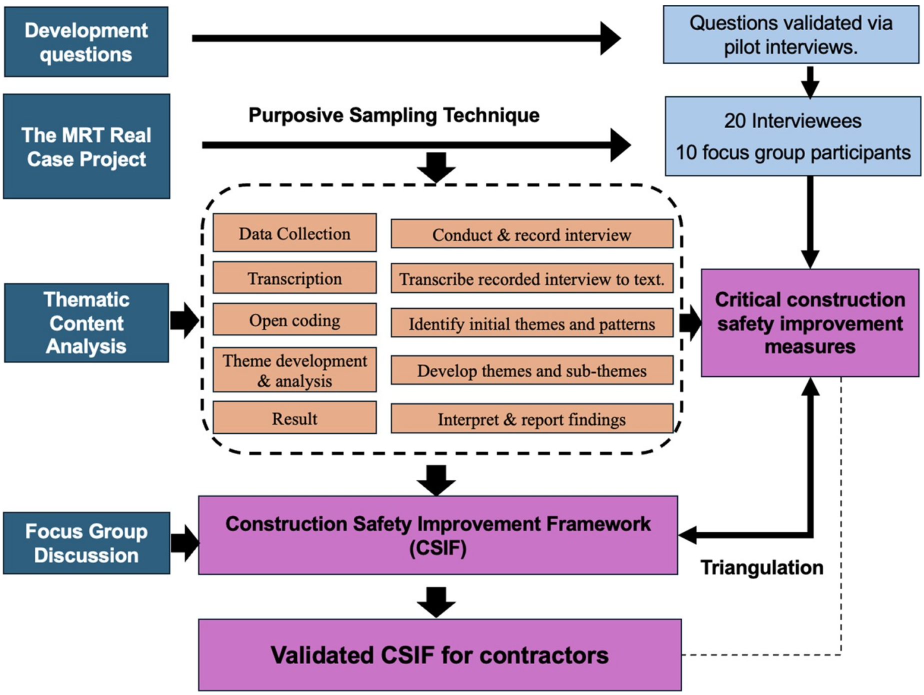

Figure 1. Qualitative research process flow
Source(s): Authors' own work (2025)

subsequently refined and narrowed to align with the study's scope. Also, semi-structured interview questions were adopted as recommended by the interviewees. Compared to unstructured and structured interviews, the semi-structured interview is more flexible and creates two-way communication between the interviewer and interviewee, allowing for in-depth information about the research topic or issue (Ohueri *et al.*, 2023). The main interview was conducted with construction experts participating in the MRT real case project.

The case study and qualitative approaches were selected because they are well-suited for exploring complex, context-specific phenomena such as construction safety in MRT projects. The case study approach enabled an in-depth investigation of real-life construction scenarios, allowing the research to identify and analyze safety measures within their operational context. The qualitative methodology aligned with the research design by providing rich, detailed data through interviews and thematic analysis, which are essential for understanding nuanced safety challenges and practices. An interview protocol was structured to explore key areas related to construction safety improvement, including current safety practices and their effectiveness; challenges faced in implementing safety measures; stakeholders' perspectives on safety culture; factors influencing safety outcomes; and the interview protocol included open-ended questions to encourage in-depth discussions and probe follow-up questions to gather detailed insights.

The interviews were conducted over two months, each lasting approximately 45–60 min, depending on the participant's availability and depth of responses. The main constraint for data collection was organizing a suitable time for the interview as conflicts with study participants due to their busy work schedules and initial reluctance to share detailed information. However, these were addressed subsequently by offering flexible interview timings and ensuring confidentiality by reaffirming the purpose and significance of the study. The sampling size was determined using the principle of data saturation, where additional interviews no longer yielded new information or themes. A total of 20 participants were included, which was sufficient to achieve a comprehensive understanding of the research questions. Participants were included in the study if they had direct experience in safety management for MRT construction projects and at least ten years of industry experience. Exclusion criteria included professionals not involved in MRT projects or lacking safety management responsibilities. This ensured that the data collected was relevant and insightful.

In relation to confidentiality, study participants' rights were protected through informed consent, obtained before the interviews. Confidentiality was maintained by storing data securely and anonymizing participant information in the analysis and reporting stages. Participants were assured that their responses would be used solely for academic purposes. Ethical issues noticeably seen from participants who felt comfortable discussing sensitive issues related to safety failures. However, this was managed successfully by creating a non-judgmental environment, ensuring confidentiality and clarifying that this research (data collection) is aimed to improve safety, not concerning assign blame.

Study biases were managed by maintaining a reflexive research approach, which involved regularly reflecting on personal assumptions and preconceptions. Data triangulation was also used by combining interviews with secondary data, such as project documentation and safety reports to validate the research findings. The data was coded using the thematic analysis method. A six-phase process was followed: familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining, and naming themes and producing the final report. This systematic approach ensured the identification of meaningful patterns.

The limitations of this study include reliance on qualitative data, which may be subject to interpretation bias and its focus on MRT projects in Malaysia, limiting the generalization of findings to other contexts and different continents or countries. Additionally, the sampling size is relatively small and may not fully capture the diversity of perspectives. However, this research's strengths lie in its context-specific focus on MRT projects, offering a tailored insights into construction safety. The inclusion of public awareness as a factor is a novel contribution and the use of a robust qualitative framework ensures detailed and actionable findings. The proposed CSIF provides practical values for improving safety practices in future projects.

4. Mass rapid transit real case construction project

The MRT projects are significant infrastructure initiatives designed to provide efficient, rapid transit systems in urban areas. In Malaysia, MRT projects have been instrumental in addressing the country's growing transportation needs, aiming to reduce traffic congestion and improve urban mobility, particularly in major cities like Kuala Lumpur. As reported by the *New Straits Times*, the construction of the MRT is projected to incur a cost of about RM46bn and is recognized as the most expensive construction endeavor in Malaysian history. As reported by Mass Rapid Transit Corporation (2023), the projects consist of three lines: MRT Circle Line within Kuala Lumpur, MRT Klang and MRT Putrajaya, covering over a 20 km radius to service high-density areas that are not serviced by any rapid transit system, as illustrated in Figure 2.

The MRT project currently has about 90 new stations, of which 26 will be in the city center and provide ridership capacity to two million passengers daily. This massive project comes with its shortcomings, especially in terms of accidents. The DOSH received reports of 34 occupational accidents during the initial four years of the MRT project. These incidents encompassed eight fatal accidents, seven cases of permanent disability and 19 instances of temporary disability (Juhari and Arifin, 2020), making it an ideal real case project for this study. Considering that the MRT projects consist of several construction firms and enormous contractors, this study applied a purposive sampling technique to select research samples from the population.

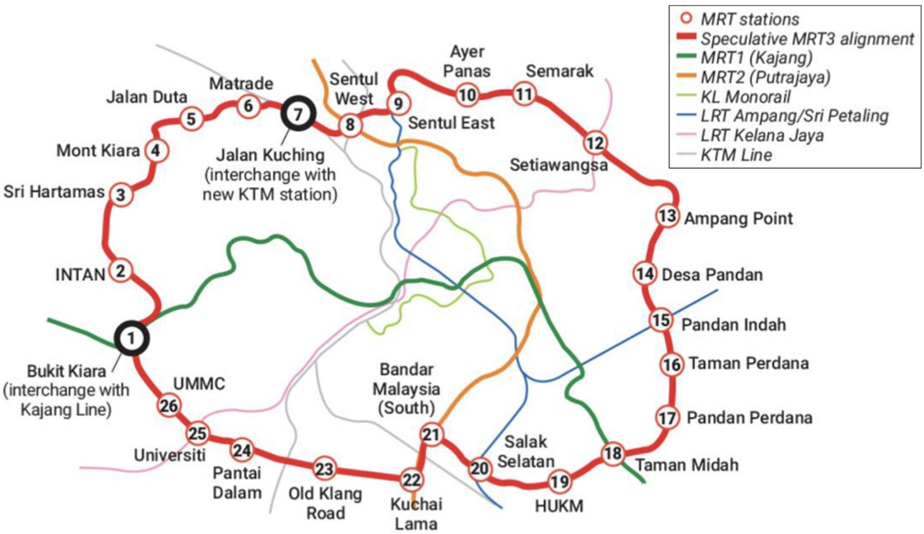

Figure 2. Mass rapid transit (MRT) case study project
Source(s): The Star online graphics (2021); https://malaysia.news.mr

Purposive sampling was chosen due to the method allowing researchers to focus on individuals or groups who can provide the most relevant, rich and detailed information about the topic under investigation. Unlike random sampling, purposive sampling method does not aim to ensure representativeness of the broader population. Instead, it prioritizes depth and insight by including participants who meet predefined criteria, such as expertise, experience or involvement in a particular context. For example, in a study on construction safety, participants may be chosen based on their roles as contractors, safety managers or site supervisors within specific construction projects. Purposive sampling is also particularly useful in qualitative research, where the goal is to explore complex phenomena, generate detailed understandings and uncover meaningful patterns. It enables researchers to maximize the value of their data by engaging with individuals who are most likely to contribute to addressing the research questions. Hence, 20 interviewees were carefully selected for the in-depth interview, comprising contractors, engineers and safety managers in MRT projects to inform the development of CSIF. The demographic information of the selected samples is provided in Table 2.

Table 2 highlights the wealth of experience possessed by the 20 interviewees, including contractors, engineers and safety managers from three companies involved in the MRT construction project. Noteworthy is that some respondents bring in a substantial 30 years of work experience, underscoring their well-seasoned viewpoints. After the interview, ten contractors and safety managers were selected for FGDs to validate CSIF, ensuring it covers all relevant aspects of contemporary safety measures beyond the state of the art. This resonates

Table 2. Demography of interviewees and company profile

Interviewee	Years of experience	Position	Company's safety certification achieved	Certification body/year
Construction Company 1				
Interviewees 1, 2, 3 and 4	20	Contractors	Certificate of Achievement (Rating of 4 Star)	NIOSH. 2004
Interviewees 5 and 6	15		The Malaysian construction excellence award	CIDB Malaysia. 2016
Interviewee 7	10		National institute of occupational safety and health (NIOSH) excellence award (gold winner)	
Construction Company 2				
Interviewees 8, 9 and 10	Between 25 and 30	Contractors	Occupational safety and health management systems (OHSAS)	CIDB Malaysia. 2015
Interviewees 11 and 12	15	Sub-Contractors	The Malaysian construction excellence award	
MRT Corp standard and compliance division				
Interviewees 13, 14 and 15	10–13	Site engineer	Environmental management system (EMS) certification	Standards and industrial research institute of Malaysia quality assurance services (SIRIM QAS)
Interviewees 16, 17 and 18	15–20	Safety manager		
Interviewees 19, 20	18	Civil engineer		

Source(s): Authors' own work (2025)

with Sekaran and Bougie's (2016) suggestion to engage knowledgeable participants for credible research outcomes. Following this, the transcriptions of the interviews are presented, capturing these insightful perspectives. Combining in-depth interviews and FGD enhances the data richness and trustworthiness of the research findings (Lambert and Loiselle, 2008).

In qualitative research, the adequacy of sample size is determined when there is no longer new information emerging from data collection. Rather than determining the number of study participants, the study acquired data saturation with no new study themes emerging in the interviews and FGD. This is the point where the sampling of 20 participants of the interview and ten focus group members is considered appropriate as empirical evidence when data saturation is achieved to ensure the scientific rigor of the study. Recent studies have explored the relationship between sample size and data saturation in qualitative research. According to Hennink and Kaiser (2022), code saturation or the point at which no new codes are identified was often reached within 9–17 interviews, while FGDs achieved saturation within 4–8 sessions, particularly in studies with homogenous populations and narrowly defined objectives.

Additionally, a similar study assessed saturation in FGDs and found that while initial code saturation could be achieved with a few groups, a more comprehensive understanding of the issues required additional sessions. They concluded that the number of focus groups needed to reach saturation would also depend on factors such as group stratification and the complexity of the research topic (Hennink, Kaiser and Marconi, 2017). This research used a systematic method to evaluate data saturation such as iterative data analysis and constant comparison of emerging themes to substantiate the adequacy of their sample sizes in qualitative research. Document data from the case studies were also assessed for data saturation to ensure that the sample size is sufficient for this study's objectives. With the evidence of saturation, the scientific basis of the study is strengthened, therefore eliminating concerns about the completeness and reliability of research findings.

5. Thematic content analysis

Thematic content analysis was adopted to analyze the qualitative data collected in this study. As viewed by Masrom *et al.* (2024), thematic content analysis involves the systematic coding and categorization of data to identify reoccurring themes, which are then organized into meaningful patterns. The thematic analysis applied in this study adhered to a systematic five-step approach outlined in studies by Neuendorf (2018). First, a face-to-face interview was conducted and recorded via the iPhone Operating System (iOS) recording device to reduce the chances of information misinterpretation that could jeopardize the authenticity of this research. The interviewees gave their consent to record the interview. Then, the recorded interview was transcribed into text. Subsequently, the data was meticulously coded to reveal emerging themes and patterns. Main and sub-themes were then identified within the coded data. Ultimately, the research team systematically analyzed and interpreted these identified themes, resulting in the identification of construction safety improvement measures.

Following this, the optimal connections is established between the established measures, resulting in the development of a CSIF for contractors. The developed framework was validated via FGD. This enabled the researcher to comprehensively understand individual perspectives and group dynamics, leading to richer insights and a more nuanced understanding of the research topic (Edley and Litosseliti, 2010). Data from the interview and FGD was triangulated and cohesively interpreted (Ohueri *et al.*, 2023), validating CSIF. The essence of validating CSIF is to ensure its practical relevance and effectiveness in reducing safety in construction sites. Validating research output helps confirm its reliability and accurately captures its applicability, strengthening the overall rigor and credibility of the research findings (Birkenmaier *et al.*, 2023).

6. Research findings

The first interview question was about gamified safety training practices for the construction workforce. Interviewees 3, 8 and 10 suggested using virtual reality to train the construction workforce via simulations for immersive hazard response. Similarly, Interviewee 12 pointed out that "*augmented reality practices, such as treasure hunts, can be used for safety education for construction workers.*" The importance of using blockchain-based incentives for contractors that comply with safety regulations was highlighted by Interviewees 16, 17 and 18, who are safety managers. According to Interviewee 18, "*Safety compliance should be made attractive, at least at the initial stage of the project, using advanced and transparent techniques.*" As postulated by Interviewee 15, "Contractors should try novel and practically effective means to ensure safety in construction sites." In support of this assertion, Interviewees 13 and 14 suggested that contractors should use neurofeedback-enhanced brain training games to regulate cognitive functions, potentially reducing accident risks and enhancing safety awareness.

Another fundamental safety measure elaborated upon by the interviewees is the mental health of construction workers. Interviewees 3, 9 and 19 stressed the need to apply modern technologies, such as CRISPR-Cas9 technology, to modify genetic factors associated with mental health disorders. This practice has the novel potential to prevent depression, anxiety or schizophrenia, which have contributed to accidents on construction sites. However, Interviewees 20 and 7 argued that most contractors do not have the financial budget for such technologies. Against that standpoint, Interview 1 stated that "*safety should be prioritized at all costs,*" suggesting the use of therapeutic means such as quantum mindfulness meditation apps and AI-powered virtual therapist avatars. He stated that "*these practices are not common and should be normalized in construction safety practices for effective management and avoidance of accidents related to the mental health of construction workers.*" Notably, Interviewee 14 recommended using biofeedback-controlled brainwave techniques to help workers maintain focus and manage stress levels, thereby improving their decision-making. He says, "*Sound decision-making reduces accident risks, thereby safeguarding the workers and public.*"

A consensus emerged among the interviewees regarding the importance of leveraging technological advancements as a dynamic's safety measure in construction projects. Interview 17 stated, "*While several technologies have been established to effectively manage safety issues, their adoption and implementation in construction practices remain low.*" He advised employing a competent workforce before implementing advanced technologies such as quantum computing for real-time risk prediction and swarm robotics for dynamic hazard detection. He continued, "*These novel technologies have been proven to effectively reduce accidents in other industries such as aviation, healthcare, etc.*" Interviewees 2, 3 and 17 acknowledged the transformative potential of cutting-edge tools like Blockchain for transparent safety compliance monitoring. Interview 20 suggested that adequate safety measures require the contractors to do things differently, beyond business as usual. He stated:

> Ambitious approaches such as Nanotechnology ought to be employed to autonomously detect and repair structural damage, reducing the risk of accidents and ensuring the longevity of infrastructure on construction sites.

Environmental health measures were collectively recognized by the interviewees as a critical factor for the safety of construction workers, especially in complex projects. Interviewees 1 and 13 pointed out the value of genetically engineered microbes for bioremediation. Interviewee 13 stated that "*bioremediation involves breaking down hazardous contaminants on construction sites, reducing environmental risks such as soil and water pollution, and minimizing potential health hazards to workers and surrounding communities.*" Similarly, nanotechnology was mentioned again as a means of self-cleaning surfaces. Other novel practices were suggested by Interviewees 6 and 16, such as atmospheric water harvesting systems to minimize harmful substances from the atmosphere and vertical farming towers for biodiversity conservation.

Interviewees agreed that emergency preparedness is a crucial measure in construction safety practices, but it is rarely discussed and practiced. According to Interviewees 1, 9 and 11, contractors should be informed on practical emergency actions and measures and predictive analytics for proactive emergency response planning and hyperloop-based rapid evacuation systems. Interviewees argued that construction accident fatalities could have been reduced with the proper emergency practices. Interviewee 8 gave instances of the building collapse, where construction workers were trapped in the rubble, and no workers, including site engineers, had any clue on emergency practices to save some of the victims. Similarly, Interviewee 5 hammered on emergency practices using quantum encryption for secure emergency communication and AI-powered drone swarms for emergency supplies delivery. Interviewee 5 stated, *"Certainly, these are not regular safety practices in the construction sector but have significantly contributed to saving lives in industries such as manufacturing and automobile."*

7. Focus group discussion and validation of construction safety improvement framework

Based on the transcribed interview data, themes and sub-themes of construction safety measures were identified, resulting in the development of the initial CSIF with findings illustrated in Table 3. The established framework was then evaluated by ten selected contractors for FGD to ascertain the relevance of CSIF in industry practices, using the ongoing MRT projects as a case study. The FGD participants evaluated the identified sub-elements of CSIF and revised them, accordingly, considering several factors, including cost, technical expertise, compatibility with existing systems, risk and sustainability.

8. Development of the construction safety improvement framework for contractors

The validated CSIF integrates key findings from in-depth interviews and FGDs, ensuring a comprehensive and practical approach to enhancing safety performance among contractors. The framework, as depicted in Figure 3, consists of five main safety improvement measures, each addressing critical aspects of construction site safety. These measures encompass regulatory compliance, safety training and education, hazard identification and risk management, technological advancements and safety culture development. By incorporating these elements, the CSIF provides a structured approach to mitigating safety risks, improving contractor awareness and fostering a proactive safety environment. The 20 sub-measures further refine these categories, offering targeted strategies such as mandatory safety training programs, real-time hazard monitoring, digital safety reporting and leadership-driven safety initiatives. Through this multi-layered approach, the framework ensures that safety improvements are not only implemented but also sustained through continuous monitoring and adaptation.

A key strength of the validated CSIF is its emphasis on both reactive and proactive safety management strategies. Reactive measures focus on incident response, accident investigation and corrective actions, ensuring that lessons learned from past incidents inform future safety protocols. On the other hand, proactive strategies emphasize preventative measures, such as predictive analytics for hazard identification, the integration of AI-driven safety monitoring and real-time worker feedback mechanisms. Additionally, the framework highlights the importance of a safety-centric organizational culture, where management

Table 3. Validation of CSIF via focus group discussion

Initial measures of CSIF	Focus group discussion	Triangulation of findings
Gamified training		
Virtual reality simulations for immersive hazard response training	FGD participants unanimously endorsed the established measures	Interview data and focus group discussion outcomes converge, ensuring the validity and reliability of the established measures
Augmented reality treasure hunts for safety learning	AR skill stimulator	AR skill stimulator to navigate complex projects
Blockchain-based incentive systems for safety compliance	Endorsed	Interview data and focus group discussion outcomes converge
Neurofeedback-enhanced brain training games	Endorsed	Interview data and focus group discussion outcomes converge
Technological advancements		
Quantum computing for real-time risk prediction	Endorsed	Interview data and focus group discussion outcomes converge
Swarm robotics for dynamic hazard detection		
Blockchain-enabled safety compliance monitoring		
Nanotechnology for self-repairing construction materials		
Mental health support		
CRISPR-based genetic therapy for mental health	VR therapy with personalized avatars	Proposed FGD suggestion not effective. Initial measures applied
Quantum mindfulness meditation apps	Endorsed	Interview data and focus group discussion outcomes converge
AI-powered virtual therapist avatars	Endorsed	Interview data and focus group discussion outcomes converge
Biofeedback-controlled brainwave techniques	Neuro feedback with gamification:	Duplication of safety measures: already mentioned under gamified training. Initial measures applied
Environmental health		
Genetically engineered microbes for bioremediation	Microbial air filtration systems:	Similar concept. However, initial safety measure is applied
Nanotechnology for self-cleaning surfaces	Endorsed	Interview data and focus group discussion outcomes converge
Atmospheric water harvesting systems	Endorsed	Interview data and focus group discussion outcomes converge
Vertical farming towers for biodiversity conservation	Endorsed	Interview data and focus group discussion outcomes converge
Emergency preparedness		
Predictive analytics for proactive emergency response planning	Wearable health monitors with emergency response function:	FGD outcome applied
Hyperloop-based rapid evacuation systems	3D-printed emergency shelters	FGD outcome will incur more cost. Initial safety measures applied
Quantum encryption for secure emergency communication	Endorsed	Interview data and focus group discussion outcomes converge
AI-powered drone swarms for emergency supplies delivery	Endorsed	Interview data and focus group discussion outcomes converge

Source(s): Authors' own work (2025)

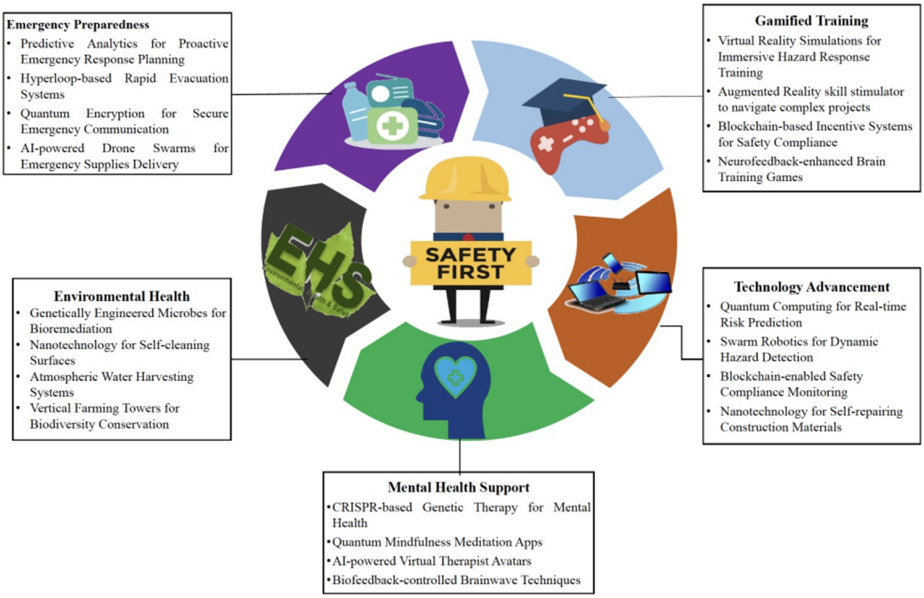

Figure 3. Construction safety improvement framework
Source(s): Authors' own work (2025)

commitment, worker engagement and communication channels are strengthened to reinforce safe work practices. By aligning contractors with best practices in safety management, the CSIF not only enhances worker protection but also improves overall project efficiency by minimizing delays caused by workplace accidents. Ultimately, this structured framework serves as a practical guide for contractors seeking to elevate safety standards, reduce incidents and create a safer construction environment.

8.1 Gamified training

While gamified training has been widely used by manufacturing, aviation and defense, its implementation for construction safety has been underexplored in literature and industry practice. Gamified training provides construction workers with virtual hands-on safety training beyond theoretical or real-life hazardous training that could expose workers to danger (Guimarães *et al.*, 2023). Immersive virtual reality, for instance, pushes the boundaries of hazard response training, enabling construction workers to confront realistic dangers during construction practices. Bao *et al.* (2024) proposed an incentive mechanism based on blockchain technology to encourage VR-based safety training. Blockchain-based incentive systems introduce novel mechanisms for rewarding and reinforcing safety compliance, fostering a culture of accountability and participation among workers. On the other hand, VR provides unique safety training scenarios and a flexible virtual environment that enables users to acquire knowledge and gain experience in construction safety practices for informed decision-making in real-life projects. According to Rivera *et al.* (2024), AR simulates a safe learning environment, engaging workers in interactive activities that promote hazard recognition and safe behavior practices. Another novel safety approach is the neurofeedback-enhanced brain training games, which empower workers to develop cognitive resilience and stress management techniques, equipping them with the mental fortitude to navigate challenging situations effectively (Corrado *et al.* (2024). Embracing these underexplored cutting-edge gamified training approaches will enable contractors to proactively address safety challenges and embrace a safety-conscious workforce, ultimately creating a safer construction environment.

8.2 Technological advancements

Technology advancement has the potential to revolutionize the evolving construction practices for effective safety management. Quantum computing provides contractors with real-time sensor data from building structures, materials, equipment, etc., predicting potential hazards like structural failures or malfunctions before occurrence (Bova *et al.*, 2021). Swarm robotics adds another layer to protect the construction workforce by patrolling the construction sites to identify leaks, unstable excavations and other potential risks faster than human inspections (Jahanshahi, *et al.*, 2017). The importance of transparency among managers, contractors and workers in implementing safety measures has been emphasized. Hence, blockchain ensures accountability and transparency when complying with safety regulations. This is made possible via secure recording and verification of safety protocols, certification and incident reports, which ensures a safety and trust culture in the construction process (Bao *et al.*, 2024). Nanotechnology for self-repairing construction materials is a future-focused proactive construction measure that transcends existing safety management. Nanotechnology has the potential to automatically detect and heal micro-cracks before they become significant safety hazards (Tohlob and Morsi, 2024).

8.3 Mental health support

Construction accident mitigation efforts have focused on physical hazards, with less attention on mental health interventions in the workforce. With advanced mental health support technology like clustered regularly interspaced short palindromic repeats (CRISPR)-based genetic therapy, the construction workforce experiences a long-term improvement in their mental well-being, reducing the risk of accidents caused by impaired cognitive functions or emotional disasters (Zhang, *et al.*, 2024). In addition, CRISPR/Cas9 is a unique genome editing tool that is potentially applied in a wide range of applications, including gene therapy and diagnostic among workers at site (Tyumentseva *et al.*, 2023). Another notable approach to managing construction workers' stress is the use of quantum mindfulness meditation apps, which promote mental resilience and stress reduction among workers, enhancing their ability to focus on safety protocols and cope with the demands of construction work (Goodings *et al.*, 2024). Beyond the common construction safety literature and practices, AI-powered virtual therapist avatars are proposed to provide personalized mental health support and counseling services. This ensures that workers are offered timely and confidential assistance once needed (Bansal and Bhattacharya, 2024). Furthermore, biofeedback-controlled brainwave techniques ought to empower workers to regulate their stress levels and enhance their cognitive performance through real-time feedback on brainwave activity, ultimately fostering a safer and healthier work environment. CRISPR-Cas9, a gene-editing technology, is primarily used in medical and biological sciences to modify DNA sequences. While its application in construction safety is not immediately apparent, one possible connection could be its potential role in occupational health improvements. For instance, future advancements in gene editing could lead to the development of genetic resilience to hazardous environmental exposures, such as reducing susceptibility to airborne contaminants, toxic chemicals or extreme heat stress – common risks in construction sites. Additionally, CRISPR-based innovations might contribute to personalized protective measures, where workers with specific genetic predispositions to certain occupational diseases could receive tailored safety protocols or medical interventions. However, these applications remain speculative and may not have immediate relevance to current construction safety frameworks.

Similarly, quantum computing is an emerging field that focuses on leveraging quantum mechanics to perform complex calculations at unprecedented speeds. Its relevance to construction safety lies in its potential to enhance predictive modeling, risk assessment and real-time hazard detection by processing vast amounts of data more efficiently than classical computing methods. For example, quantum algorithms could enable advanced simulations of construction site conditions, allowing for highly accurate risk prediction models that consider multiple variables, such as weather conditions, worker fatigue and structural integrity. Additionally, quantum-enhanced machine learning could optimize safety decision-making processes, enabling proactive hazard identification and response strategies. However, the practical application of quantum computing in construction safety remains in its early stages, as the technology is not yet widely accessible or integrated into industry standards. To strengthen the discussion, it would be beneficial to provide concrete examples or case studies demonstrating how these technologies are currently being explored for safety management in high-risk industries, ensuring their relevance is clearly articulated within the study.

8.4 Environmental health

Compared to the traditional approach, groundbreaking approaches are recommended to provide a paradigm shift in construction projects' environmental health and safety management. Issues of soil and water contamination are controlled using genetically engineered microbes. According to Pant *et al.* (2021), this innovative approach effectively mitigates environmental hazards in construction sites and ensures the health and safety of workers and the public. As mentioned earlier, Nanotechnology offers not only self-repair but also self-cleaning surfaces. This new paradigm in surface hygiene minimizes the accumulation of harmful substances and reduces the risk of slips and falls (Tohlob and Morsi, 2024). Its impact in streamlining maintenance efforts and enabling workers to focus on the core tasks without compromising their well-being is noteworthy. Another significant environmental health and safety measure is atmospheric water harvesting systems. The cutting-edge technology provides a sustainable solution for water sourcing, significantly mitigating risks associated with water scarcity and contamination (Entezari, *et al.*, 2023). According to Zaręba *et al.* (2021), vertical farming towers for biodiversity conservation were identified as a multifaceted approach to creating green spaces that promote biodiversity, improve air quality and provide fresh produce for workers.

8.5 Emergency preparedness

Emergency preparedness has been ignored despite the potential to save accident victims and reduce the number of fatalities. To promote emergency practices, predictive analytics for proactive emergency response planning was recommended for identifying potential emergencies and allowing timely allocation of resources and quick response to save accident victims (Hernandez and Roberts, 2020). This is complemented via hyperloop-based rapid evacuation systems. According to Lang *et al.* (2024), hyperloop-based rapid evacuation systems provide contractors with an efficient and rapid evacuation route that has the potential to minimize fatalities during emergencies like structural collapse and natural disasters. Another critical aspect of emergency preparedness is the swift communication between the necessary emergency units and those at the accident scene. Jahanshahi *et al.* (2017) reiterate that quantum encryption offers more secure emergency communication, guaranteeing that the emergency calls are not false alarms. This prompts a fast response from the emergency team. Besides, the study by Bova *et al.* (2021) supports using AI-powered swam robots to supply essential first aid equipment to areas humans cannot reach due to the potential threat of more collapse. This approach is underexplored in existing safety improvement measures.

This shows that regulatory bodies can integrate safety improvement measures into existing safety standards, in which government agencies, construction authorities and safety regulators can incorporate technology-driven safety measures into existing laws and guidelines. Furthermore, discuss potential policy updates that could support the implementation of digital safety reporting, AI-powered risk assessments or mandatory safety training using virtual simulations. Highlight examples of regulatory frameworks (such as OSHA, CIDB Malaysia or DOSH) that could evolve to accommodate these innovations.

For feasibility, consideration on factors such as cost, infrastructure requirements and contractor readiness to adopt these measures. Possible government incentives, funding mechanisms or mandatory compliance programs that could facilitate adoption. For scalability, elaborate on how these safety improvements can be adapted for different project sizes, from small contractors to large-scale infrastructure projects. Pilot programs or phased implementation strategies to ensure smooth integration into the industry. Therefore, it shows how regulatory bodies can drive the adoption of safety improvements, making the framework more actionable and policy-relevant.

9. Conclusions

Construction accidents and increasing fatalities have prompted the need for effective construction safety measures beyond state of the art to align with evolving construction practices. Thus, this study extends the safety improvement practices in complex construction projects by incorporating cutting-edge safety measures to enable contractors to effectively manage site safety. A case study of the MRT project in Malaysia was applied to actualize the aim of this research. Qualitative research methods of in-depth interviews and FGDs with practitioners of MRT projects were carried out. The data were analyzed using thematic content analysis. Hence, construction safety measures were identified and validated, developing the CSIF. CSIF encompasses five main construction safety measures: gamified training, mental health support, technological advancements, environmental health and emergency preparedness. The numerous sub-elements discussed in this study go beyond the state-of-the-art safety measures in existing literature and industry practices, providing practitioners with a novel, comprehensive and proactive approach toward effective safety management. Also, this study enriches the theoretical foundation of construction safety by focusing on recent advancements, deepening the understanding of safety practices in complex projects. The study is limited to qualitative research. Therefore, further study is proposed to apply quantitative research and statistical analysis to examine the correlation between the established safety measures.

9.1 Implications of research

The findings of this study contribute significantly to the theoretical understanding of construction safety, particularly in the context of MRT projects. By exploring safety measures currently used on MRT construction sites, this study expands the theoretical framework of safety management by incorporating Malaysia-specific safety practices. The study introduces the novel consideration of public awareness as a critical factor influencing safety measures, which has been overlooked in previous research with new theoretical insight enriches the broader discourse on safety culture. Additionally, the study challenges existing theoretical models by demonstrating that practicality, a factor traditionally emphasized in the safety literature, may have limited influence in MRT projects due to the prequalification criteria for contractors, thus providing nuanced insights into the role of project complexity in shaping safety measures.

9.2 Practical implications

For industry practitioners, this research provides a practical roadmap to enhance safety measures on MRT construction sites in Malaysia. The proposed CSIF offers contractors a structured approach to evaluate and improve safety practices, tailored to the unique safety culture and operational dynamics of MRT projects. By identifying critical factors such as human behavior, workplace conditions, documentation, government policies, unpredictability and public awareness, the framework enables contractors to develop comprehensive safety strategies that are both proactive and context-specific. Moreover, the emphasis on public awareness addresses a critical gap in current safety practices, ensuring safer construction operations. This practical tool not only supports contractors in meeting regulatory requirements but also fosters a culture of continuous improvement, ultimately contributing to safer and more efficient construction processes in MRT and other large-scale infrastructure projects.

References

Ahmed, S. and Hoque, I. (2018), "Investigation of the causes of accidents in construction projects", *Journal of System and Management Sciences*, Vol. 8 No. 3, pp. 67-89.

Ali, H. and Omran, A. (2016), "Strategies for improving the safety performance of construction contractors", *Annals of the Faculty of Engineering Hunedoara*, Vol. 14 No. 1, p. 109.

Awolusi, I.G. and Marks, E.D. (2017), "Safety activity analysis framework to evaluate safety performance in construction", *Journal of Construction Engineering and Management*, Vol. 143 No. 3, p. 5016022.

Ayob, A., Shaari, A.A., Zaki, M.F.M. and Munaaim, M.A.C. (2018), "Fatal occupational injuries in the Malaysian construction sector-causes and accidental agents", *IOP Conference Series: Earth and Environmental Science*, Vol. 140 No. 1, p. 12095.

Bansal, D. and Bhattacharya, N. (2024), "Artificial intelligence and metaverse applications in the healthcare sector", *Multi-Sector Analysis of the Digital Healthcare Industry*, IGI Global, Hershey, pp. 110-132.

Bao, Q.L., Tran, S.V.T., Yang, J., Pedro, A., Pham, H.C. and Park, C. (2024), "Token incentive framework for virtual-reality-based construction safety training", *Automation in Construction*, Vol. 158, p. 105167.

Birkenmaier, L., Lechner, C.M. and Wagner, C. (2023), "The search for solid ground in text as data: a systematic review of validation practices and practical recommendations for validation", *Communication Methods and Measures*, pp. 1-29.

Bova, F., Goldfarb, A. and Melko, R.G. (2021), "Commercial applications of quantum computing", *EPJ Quantum Technology*, Vol. 8 No. 1, p. 2.

Buniya, M.K., Wuni, I.Y., Yousif, O.S. and Al-Mhdawi, M.K.S. (2024), Quantifying the impact index of key barriers to safety program initiatives in the Iraqi construction industry, *Construction Innovation*, doi: 10.1108/CI-08-2023-0185.

Corrado, S., Tosti, B., Mancone, S., Di Libero, T., Rodio, A., Andrade, A. and Diotaiuti, P. (2024), "Improving mental skills in precision sports by using neurofeedback training: a narrative review", *Sports*, Vol. 12 No. 3, p. 70.

Creswell, J.W. (1998), “Applies the standard of verification in 5 traditions: biography (p. 204-207); phenomenology (207-208); grounded theory (208-210); ethnography (210-213; and case study (213-215)”,

Department of Occupational Safety and Health (DOSH) (2023), “Construction safety division and construction work section”, available at: www.dosh.gov.my/index.php/construction-safety-v/introduction

Department of Occupational Safety and Health (DOSH) (2024), “Safety and health enforcement in Malaysia”.

Duc, N.A. (2024), “Understanding the correlates of construction safety of high-rise buildings: a Bayesian perspective”, *Journal of Science and Technology in Civil Engineering (JSTCE) – HUCE*, Vol. 18 No. 1, pp. 68-81.

Duryan, M., Smyth, H., Roberts, A., Rowlinson, S. and Sherratt, F. (2020), “Knowledge transfer for occupational health and safety: cultivating health and safety learning culture in construction firms”, *Accident Analysis and Prevention*, Vol. 139, p. 105496.

Ebekozien, A., Aigbavboa, C., Samsurijan, M.S., Radin Firdaus, R.B. and Rohayati, M.I. (2023), “Investigating safety violations on Nigerian construction sites”, *International Journal of Construction Management*, Vol. 24 No. 13, pp. 1-11.

Edley, N. and Litosseliti, L. (2010), “Contemplating interviews and focus groups”, *Research Methods in Linguistics*, Vol. 155, p. 179.

Entezari, A., Esan, O.C., Yan, X., Wang, R. and An, L. (2023), “Sorption-based atmospheric water harvesting: materials, components, systems, and applications”, *Advanced Materials*, Vol. 35 No. 40, p. 2210957.

Frimpong, S., Riza, Y.S., Cynthia, C.W., Elijah, F.B., Ayirebi, D. and Rasaki, K.F. (2025), “A scoping review of research on mental health conditions among young construction workers”, *Construction Innovation*, Vol. 25 No. 1, pp. 5-34.

Giri, O.P., Poudel, K. and Shrestha, S.K. (2023), “Safety management in public building construction: a case study of Pokhara Valley”, *Journal of Business and Management*, Vol. 7 No. 1, pp. 90-101.

Goodings, L., Ellis, D. and Tucker, I. (2024), “Introducing mental health apps”, *Understanding Mental Health Apps: An Applied Psychosocial Perspective*, Springer Nature Switzerland, Cham, pp. 1-22.

Guimarães, A., Cavalcanti, M. and Vasconcelos, B.M. (2023), “Gamification using technologies for occupational safety training in the civil construction sector”, *Work*, pp. 1-9.

Hadi, P.Y.P., Soetjipto, J.W. and Trisiana, A. (2024), “Implementation of construction safety plan in the building project”, *Rekayasa Sipil*, Vol. 18 No. 1, pp. 24-30.

Harahap, M.I.P., Othman, I. and Dinata, N.A.M. (2024), “Investigation on the nature of safety rule violations in high-rise construction projects”, *Journal of Advanced Research in Applied Sciences and Engineering Technology*, Vol. 41 No. 2, pp. 164-179.

Health and Safety Executive (HSE) (2021), “Health and safety in the workplace: regulations and guidance”.

Health and Safety Executive (HSE) (2024a), “The cost to Britain of workplace injury and illness 2022/23”, available at: www.hse.gov.uk/statistics/cost.htm

Health and Safety Executive (HSE) (2024b), “Workplace fatal injuries in great Britain 2023/24”, available at: www.hse.gov.uk/statistics/fatals.htm

Heinrich, H.W. (1931), *Industrial Accident Prevention: A Scientific Approach*, McGraw Hill Book Company, New York, NY.

Hennink, M.M. and Kaiser, B.N. (2022), “Sample sizes for focus group discussions: a systematic review of the literature”, *Qualitative Health Research*, Vol. 32 No. 4, pp. 617-628.

Hennink, M.M., Kaiser, B.N. and Marconi, V.C. (2017), “Code saturation versus meaning saturation: how many interviews are enough? ”, *Qualitative Health Research*, Vol. 27 No. 4, pp. 591-608.

Hernandez, K. and Roberts, T. (2020), "Predictive Analytics in Humanitarian Action: a preliminary mapping and analysis", K4D emerging issues report, p. 33.

Hinze, J. (1997), *Construction Safety*, Prentice-Hall, Upper Saddle River, NJ.

Hislop, R.D. (1999), "Construction site safety: a guide for managing contract".

Holt, A.S.J. (2008), *Principles of Construction Safety*, John Wiley and Sons.

Hossain, M.M., Ahmed, S., Anam, S.M.A., Baxramovna, I.A., Meem, T.I., Sobuz, M.H.R. and Haq, I. (2025), "BIM-based smart safety monitoring system using a mobile app: a case study in an ongoing construction site", *Construction Innovation*, Vol. 25 No. 2, pp. 552-576, doi: 10.1108/CI-11-2022-0296.

Hussain, R., Akeem, P., Syed Farhan, A.Z., Muhammad, S.A., Mehrtash, S. and Chansik, P. (2023), "Conceptual framework for safety training for migrant construction workers using virtual reality techniques", *Digitalization in Construction*, Routledge, London, pp. 93-103.

Indrayana, D.V., Pribadi, K.S., Marzuki, P.F. and Iridiastadi, H. (2023), "Safety leadership and performance in Indonesia's construction sector: the role of project owners' maturity", *International Journal of Safety and Security Engineering*, Vol. 13 No. 4.

International Labour Organization (ILO) (2022), "Code of practice safety and health in construction", available at: www.ilo.org/sites/default/files/wcmsp5/groups/public/@ed_dialogue/@sector/documents/normativeinstrument/wcms_861584.pdf

Jahanshahi, M.R., Shen, W.M., Mondal, T.G., Abdelbarr, M., Masri, S.F. and Qidwai, U.A. (2017), "Reconfigurable swarm robots for structural health monitoring: a brief review", *International Journal of Intelligent Robotics and Applications*, Vol. 1 No. 3, pp. 287-305.

Jain, S., Jauhar, S. and Piyush, K. (2024), "A machine-learning-based framework for contractor selection and order allocation in public construction projects considering sustainability, risk, and safety", *Annals of Operations Research*, Vol. 338 No. 1, doi: 10.1007/s10479-024-05898-6.

Juhari, M.L. and Arifin, K. (2020), "Validating measurement structure of materials and equipment factors model in the MRT construction industry using confirmatory factor analysis", *Safety Science*, Vol. 131, p. 104905.

Karakhan, A.A., Rajendran, S., Gambatese, J. and Nnaji, C. (2018), "Measuring and evaluating safety maturity of construction contractors: multi-criteria decision-making approach", *Journal of Construction Engineering and Management*, Vol. 144 No. 7, p. 4018054.

Khalid, U., Sagoo, A. and Benachir, M. (2021), "Safety management system (SMS) framework development–mitigating the critical safety factors affecting health and safety performance in construction projects", *Safety Science*, Vol. 143, p. 105402.

Lambert, S.D. and Loiselle, C.G. (2008), "Combining individual interviews and focus groups to enhance data richness", *Journal of Advanced Nursing*, Vol. 62 No. 2, pp. 228-237.

Lang, A.J., Connolly, D.P., de Boer, G., Shahpar, S., Hinchliffe, B. and Gilkeson, C.A. (2024), "A review of Hyperloop aerodynamics", *Computers and Fluids*, Vol. 273, p. 106202.

Mahmoud, A.S., Hamdan Ahmad, M., Mohd Yatim, Y. and Aminu Dodo, Y. (2022), "Safety performance framework at construction site for self-regulation by building developers", *Engineering, Construction and Architectural Management*, Vol. 29 No. 9, pp. 3394-3414.

Manu, P., Ankrah, N., Proverbs, D. and Suresh, S. (2013), "Mitigating the health and safety influence of subcontracting in construction: the approach of main contractors", *International Journal of Project Management*, Vol. 31 No. 7, pp. 1017-1026.

Manzo, J. (2017), "The $5 billion cost of construction fatalities in the United States: a 50 state comparison", The Midwest Economic Policy Institute (MEPI), Saint Paul, MN, USA, available at: https://illinoisepi.org/site/wp-content/themes/hollow/docs/wages-labor-standards/mepi-construction-fatalities-nationwide-final.pdf

Masrom, M.A.N., Ohueri, C.C., Azman, A.N. and Chan, M. (2024), "Guidelines for facilitating stakeholders roles in community engagement in green social infrastructure development", *International Journal of Sustainable Construction Engineering and Technology*, Vol. 15 No. 1, pp. 1-14.

Mass Rapid Transit Corporation (2023), *LRT Laluan Mutiara*, available at: www.mymrt.com.my/ms/

Mohandes, S.R., Durdyev, S., Sadeghi, H., Mahdiyar, A., Hosseini, M.R., Banihashemi, S. and Martek, I. (2023), "Towards enhancement in reliability and safety of construction projects: developing a hybrid multi-dimensional fuzzy-based approach", *Engineering, Construction and Architectural Management*, Vol. 30 No. 6, pp. 2255-2279.

Mohy, A.A., Bassioni, H.A., Elgendi, E.O. and Hassan, T.M. (2024), "Innovations in safety management for construction sites: the role of deep learning and computer vision techniques", *Construction Innovation*, doi: 10.1108/CI-04-2023-0062.

Neuendorf, K.A. (2018), "Content analysis and thematic analysis", *In Advanced Research Methods For Applied Psychology*, Routledge, pp. 211-223.

Ng, S.T., Cheng, K.P. and Skitmore, R.M. (2005), "A framework for evaluating the safety performance of construction contractors", *Building and Environment*, Vol. 40 No. 10, pp. 1347-1355.

Nnaji, C., Gambatese, J.A. and Eseonu, C. (2018), "Theoretical framework for improving the adoption of safety technology in the construction industry", Construction Research Congress 2018, pp. 356-366.

Noorliza, O. and Isha, A.S.N. (2023), "The role of safety culture in empowering safety behavior at rail transport industry in Malaysia: a review of literature", *Journal of Social Transformation and Regional Development*, Vol. 5 No. 1, pp. 40-50.

Occupational Safety and Health Administration (OSHA) (2022), "Commonly used statistics", available at: www.osha.gov/data/commonstats

Ohueri, C.C., Masrom, M.A.N., Habil, H. and Ambashe, M.S. (2023), "IoT-based digital twin best practices for reducing operational carbon in building retrofitting: a mixed-method approach", *Engineering, Construction and Architectural Management*, doi: 10.1108/ECAM-08-2023-0827.

Okpala, I., Nnaji, C. and Karakhan, A.A. (2020), "Utilizing emerging technologies for construction safety risk mitigation", *Practice Periodical on Structural PNTDesign and Construction*, Vol. 25 No. 2, p. 4020002.

Osei-Asibey, D., Ayarkwa, J., Adinyira, E., Acheampong, A. and Amoah, P. (2021), "Roles and responsibilities of stakeholders towards ensuring health and safety at construction site", *Journal of Building Construction and Planning Research*, Vol. 9 No. 1, pp. 90-114.

Othman, I., Majid, R., Mohamad, H., Shafiq, N. and Napiah, M. (2018), "Variety of accident causes in construction industry", *MATEC Web of Conferences*, Vol. 203, *EDP Sciences*, p. 2006.

Pant, G., Garlapati, D., Agrawal, U., Prasuna, R.G., Mathimani, T. and Pugazhendhi, A. (2021), "Biological approaches racticed using genetically engineered microbes for a sustainable environment: a review", *Journal of Hazardous Materials*, Vol. 405, p. 124631.

Reason, J.T. (1990), *Human Error*, Cambridge University Press, Cambridge.

Rivera, M.L., Mora-Serrano, J. and Oñate, E. (2024), "A critical review of how extended reality (XR) has addressed key factors influencing safety on construction projects (fSCPs)", *Archives of Computational Methods in Engineering*, pp. 1-34.

Sankar, S.S. and Anandh, K.S. (2024), "Navigating leadership styles through qualitative exploration for enhanced safety in the construction sector", *Safety Science*, Vol. 175, p. 106495.

Shabani, T., Jerie, S. and Shabani, T. (2024), "A comprehensive review of the Swiss cheese model in risk management", *Safety in Extreme Environments*, Vol. 6 No. 1, pp. 43-57.

Smallwood, J. (2017), "The impact of a client contractor health and safety (H&S) programme on contractor H&S performance", *Procedia Engineering*, Vol. 196, pp. 996-1002.

Tam, C.M., Zeng, S.X. and Deng, Z.M. (2004), “Identifying elements of poor construction safety management in China”, *Safety Science*, Vol. 42 No. 7, pp. 569-586, doi: 10.1016/j.ssci.2003.09.001.

Tan, Z.Y., Shide, K., Kanisawa, H. and Mine, N. (2022), “Factors in construction accidents and the barriers of safety practices: perspectives of contractors”, *International Journal of Social Science Research*, Vol. 4 No. 3, pp. 1-13.

Teo, E.A.L. and Feng, Y. (2011), “Costs of construction accidents to Singapore contractors”, *International Journal of Construction Management*, Vol. 11 No. 3, pp. 79-92.

Teo, A.L.E., Ofori, G., Tjandra, I.K. and Kim, H. (2016), “Design for safety: theoretical framework of the safety aspect of BIM system to determine the safety index”, *Construction Economics and Building*, Vol. 16 No. 4, pp. 1-18.

Tohlob, A.A.H. and Morsi, H.E.E.D. (2024), “Nanotechnology and its impact on achieving sustainable architecture in Egypt”, *Journal of Umm Al-Qura University for Engineering and Architecture*, Vol. 15 No. 2, pp. 1-24.

Tyumentseva, M., Tyumentsev, A. and Akimkin, V. (2023), “CRISPR/Cas9 landscape: current state and future perspectives”, *International Journal of Molecular Sciences*, Vol. 24 No. 22, p. 16077, doi: 10.3390/ijms242216077.

Versteeg, K., Bigelow, P., Dale, A.M. and Chaurasia, A. (2019), “Utilizing construction safety leading and lagging indicators to measure project safety performance: a case study”, *Safety Science*, Vol. 120, pp. 411-421.

Zabidi, H., Chijioke-Churuba, J.N., Abdullahi, S.M., Fasina, K., Ilelah, K.G., Abubakar, A., … Ogunmilua, O.K. (2024), “Environmental and public health challenges of phases towards cement production, remediation monitoring and evaluation strategies”, *Communication in Physical Sciences*, Vol. 12 No. 1, pp. 103-119.

Zailani, B.M., Moda, H., Ibrahim, Y.M. and Abubakar, M. (2023), “Improving the antecedents of non-compliance to safety regulations toward an optimized self-regulated construction environment in Nigeria”, *International Journal of Occupational Safety and Ergonomics*, Vol. 29 No. 3, pp. 1212-1219.

Zaręba, A., Krzemińska, A. and Kozik, R. (2021), “Urban vertical farming as an example of nature-based solutions supporting a healthy society living in the urban environment”, *Resources*, Vol. 10 No. 11, p. 109.

Zermane, M., Tohir, M., Baharudin, M.R. and Yusoff, H.M., (2020), “Analysis of the contributing factors for fatal accidents due to falls from heights in Malaysia and the USA”, *Pertanika Journal of Science and Technology*, Vol. 28 No. S1, pp. 15-36.

Zhang, M.L., Li, H.B. and Jin, Y. (2024), “Application and perspective of CRISPR/Cas9 genome editing technology in human diseases modeling and gene therapy”, *Frontiers in Genetics*, Vol. 15, p. 1364742.

Zoleykani, M.J., Abbasianjahromi, H., Banihashemi, S., Tabadkani, S.A. and Hajirasouli, A. (2024), “Extended reality (XR) technologies in the construction safety: systematic review and analysis”, *Construction Innovation*, Vol. 24 No. 4, pp. 1137-1164, doi: 10.1108/CI-05-2022-0131.

Further reading

Cambraia, F.B., Saurin, T.A., Bulhões, I.R. and Formoso, C.T. (2024), “A knowledge framework of participation supportive of resilient and safe construction projects: a systematic review”, *Safety Science*, Vol. 175, p. 106494.

Jato-Espino, D., Vila-Cortavitarte, M., Rodriguez-Hernandez, J. and Castro-Fresno, D. (2024), “Gamification as a tool to improve educational and training outcomes in civil engineering”, *Journal of Civil Engineering Education*, Vol. 150 No. 4, p. 3124001.

Occupational Safety and Health Administration (OSHA) (2024), “National safety Stand-Down to prevent falls in construction”, available at: www.osha.gov/stop-falls-stand-down

Shojaei, R.S., Oti-Sarpong, K. and Burgess, G. (2023), "Leading UK construction companies' strategies to tackle BIM training and skills challenges", *International Journal of Construction Education and Research*, Vol. 19 No. 4, pp. 383-404.

US Bureau of Labor Statistics (2024), "Job Requirements for construction laborers. Workplace Injuries and Job Requirements for Construction Laborers: Spotlight on Statistics: U.S. Bureau of Labor Statistics (bls.gov)".

Yang, L., Shao, L., Nie, Q. and Han, X. (2024), "Cascading failure analysis of causal factors for construction collapse accidents based on network theory", *Journal of Construction Engineering and Management*, Vol. 150 No. 2, p. 04023163.

Corresponding author
Melissa Chan can be contacted at: melissa.chan@vu.edu.au