

Article

Construction Safety Risk Assessment of High-Pile Wharf: A Case Study in China

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Abstract: The complexity of the wharf components and the harshness of the offshore construction environment increase the safety risk of hazards, which has highlighted the importance and urgency of safety risk management in high-pile wharf constructions. This paper established a visualized digital construction safety risk model for high-pile wharf based on a so-called FAHP method (the combination of fuzzy comprehensive evaluation (FCE) and analytic hierarchy process (AHP) methods). The construction safety risk indicators were constructed as the target layer, the principle layer and the scheme layer, and then the corresponding safety risk assessment algorithm was established. The physical, functional and safety risk assessment parameters of the component in the BIM model were employed to the safety risk assessment algorithm, and the risk assessment level of each sub-process was subsequently classified. The case study indicated that the high-pile wharf construction project included five elements in principle layer and 15 risk indicators in the scheme layer. Moreover, it was demonstrated that the sub-processes with the highest construction risk level were steel pipe pile sinking in wharf construction and steel pipe pile, steel sheath-immersed pile sinking and embedded rock pile construction in approaches to bridge construction with a risk level of III. In this way, the quantitative visualization of the construction safety risk was effectively realized, which facilitates the safety risk management of construction sites and timely warning and response to unexpected safety accidents.

Keywords: high-pile wharf; BIM technology; construction safety; risk evaluation; visualization



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1. Introduction

The high-pile wharf is increasingly becoming one of the most widely used structural forms due to its significant advantages such as lightweight construction, good wave reduction effect and reduced use of sand and gravel [1]. However, as a typical water transportation project, the construction of a high-pile wharf involves aerial work and underwater work. The prefabrication, transportation and installation of large components for the project involves a wide range of construction materials and machinery, which brings more and more huge challenges for the construction safety management of the project [2]. In particular, the wharf construction is usually located in the offshore and open sea area, which is greatly affected by meteorological disasters and has very complicated geological conditions [3]. The large investment amount and project scale of a high-pile wharf project leads to a long construction period and a large number of participants in the project, which leads to increased difficulty in construction and the coordination of the construction process [4]. If the materials, equipment and personnel at the construction site are not well coordinated and managed, it is likely to cause safety accidents due to insufficient safety control measures, which not only delays the construction period but also threatens the safety of personnel [5,6]. For instance, in 2020, during the construction of a general cargo terminal in Wuhu, China, a collapse occurred during the pouring of concrete

for the cantilever section of the upper crossbeam on the upstream side, which resulted in three operators who were working on the project to fall into the river, two deaths and a serious direct economic loss of more than CNY 3 million. Under the current situation of gradually increasing project scales and multiple project participants, the traditional project safety assessment and construction methods can no longer accurately and completely represent the construction situation. It is necessary to improve the construction safety risk assessment system to support the safety risk management of modern engineering projects, especially for high-pile wharf constructions.

Performing a safety risk assessment before construction is of particular significance for construction safety management. In fact, traditional safety risk management systems are designed by monitoring and investigating safety hazards that have already occurred to develop targeted countermeasures to reduce the risk of future repeat safety events [7,8]. Summarizing the causes of past accidents and the injury data of each influencing factor helps to identify safety risk signals and alerts before the start of similar projects to ensure the safe progression of the project [9]. This kind of risk assessment approach based on safety hazards that have already occurred provides an effective reference scheme for safety risk management in similar projects but at the cost of safety accidents [10]. Even so, it is possible that the causes of safety accidents may not include all the safety risk factors of the project, and the resulting safety risk analysis may not be comprehensive or universal. What is more, for high-pile wharf projects, the geographic environment and actual construction factors of each project are quite different, and the conclusions of the already existing safety risk analysis cannot be directly applied to new projects. In order to address this problem, it is more accurate to carry out a practical assessment of safety activities during the construction phase of the project and establish positive countermeasures accordingly [10]. In addition, the safety conditions at the project site can be assessed by assigning one or more trained observers on site. These measures are relatively accurate and more effective for a given project but are more dependent on the experience of the on-site assessor and the employed measurements while increasing the cost of safety management for the project.

To avoid safety incidents as much as possible, a proactive approach to safety management during the planning and construction phases of a project has become essential for large-scale engineering projects today. Predicting the safety performance of current projects and potential risks in operations or facilities in advance by utilizing quantitative means can help to take proactive measures to avoid or minimize the occurrence of accidents. Predictive indicators of safety performance that can be measured and monitored during the construction phase are identified as leading indicators, which can be measured and adjusted as the project progresses to monitor and improve safety performance. Compared to the aforementioned lagging indicators (which measure the outcome of activities or events that have occurred) summarized after a safety incident, leading indicators are more objective and comprehensive and are more useful in predicting safety risks in construction projects. However, there are still challenges in identifying the leading indicators of hazard in a high-pile wharf project prior to construction. Although some newly developed strategies, such as data mining technology, can be introduced to extract safety risk-related leading indicators from a large number of engineering data, they cannot work efficiently due to the fact that the number of high-pile wharf is generally limited and the individual differences are large [11–13]. If the construction information can be accurately collected at project sites and analyzed timely in the whole process of construction, the construction safety risk can be accordingly estimated.

Benefiting from the rapid development of information and digital technology in the construction industry, the data and information of the whole lifecycle of engineering projects can not only be effectively organized but also realize the visualized presentation of the construction digital models [14–17]. More fortunately, the digital information completely reflects all the real situation of the project and can be continuously updated as the construction progresses. Building information modeling, also called BIM, is considered an effective platform for construction informationization [18,19]. Based on the platform

constructed by BIM, the structural components and external environments in construction can be extracted and shared in time [20,21]. Moreover, the BIM model supports the data establishment, sharing and management of both static structural components as well as external environments [22]. Instead of the traditional drawings supplied by CAD, a virtual construction environment that represents the real situation of the construction site can be established based on the BIM platform [23–25]. The BIM-based system can collect information from construction sites and further attach it to the component as the property. Similarly, it is believed that safety-related information can be attached to the components in the BIM management platform as safety risk assessment property [26]. In this way, the safety risk of the construction can be quantitatively estimated in the bidding stage before construction [27]. More targeted safety management measures and emergency response plans can be developed in advance [28,29]. At the construction sites, the component properties including the safety risk assessment parameters can be updated during the construction process so that the re-estimated safety risk data will be updated in the BIM-based platform [30].

Based on the BIM platform, a safety risk identification system and early warning system for China's metro construction was established, by which the safety risk control for China's metro construction including pre-construction risk identification and risk warning in construction were visualized and quantitatively developed [31]. In recent years, some newly developed data analysis methods, such as the fuzzy hierarchical comprehensive evaluation method, the BP neural network and analytic network process–fuzzy comprehensive evaluation model have been introduced to the BIM-based platform to develop construction safety risk assessments and safety management [32–34]. During the construction of a high-pile wharf, tiny problems may cause safety accidents. In addition to developing a strict safety management system for the project, it is more important to implement safety management according to the actual situation of the construction site. With the help of project information provided by BIM, it is expected to realize the risk pre-assessment of the project, real-time on-site assessment and the formulation of effective safety emergency plans. However, efficient safety risk assessments cannot work without the support of the corresponding safety risk theory [6,11,35–37]. At present, there is still a lack of safety risk theory for the BIM platform, and investigations on safety risk assessment systems based on it have not been carried out yet.

In this paper, a BIM-based safety risk assessment system for high-pile wharf construction is established. Firstly, the safety risk assessment indicators are determined by the accident causation theory. Then, the risk assessment algorithms are implemented based on the proposed FAHP method, which combines the fuzzy comprehensive evaluation and analytic hierarchy process methods [38,39]. With the aid of the comprehensive and real-time information provided by the BIM model of high-pile wharf construction, the safety risk assessment indicators as well as the scores can be determined. Consequently, the safety risk levels of each sub-process in high-pile wharf construction can be dynamically visualized and managed, which contributes to the efficiency and safety of the construction of the high-pile wharf.

2. Theory of Safety Risk Assessment

Based on the risk management theory, there are two difficulties for the construction safety risk assessment: choosing a reasonable and effective risk evaluation index system and a risk evaluation method. The scientificity and rationality of the evaluation index system is directly related to the accuracy and comprehensiveness of the evaluation results. Choosing the appropriate risk evaluation method is the key to fully explore the engineering data and accurately reflect the project risk indicators. In order to effectively carry out a construction safety risk evaluation, it is necessary to carefully analyze the construction safety risk assessment factors to ensure the scientific rationality of the construction safety risk evaluation index system. Specifically, the identification and screening of assessment factors in high-pile wharf construction should follow the following principles:

- (1) Systematic principle. The construction safety risk-influencing factors should cover all aspects of the construction management of high-pile wharves and at the same time conform to the actual situation of the construction industry and the construction characteristics of high-pile wharves.
- (2) Principle of independence. To determine the relationship between the influencing factors, it is necessary to require that these factors are independent of each other. Therefore, it is especially important to select the appropriate influencing factors.
- (3) Targeted principle. The construction safety risk-influencing factors of high-pile wharf projects are numerous and quite complicated. Therefore, the factors with greater influence and representativeness should be selected in a targeted way.
- (4) Dynamic principle. Project construction is a dynamic and real-time changing process. Assessment indicators should be selected based on the actual project situation for dynamic identification, and evaluation indicators need to be constantly updated to satisfy the needs of high-pile wharf construction safety risk evaluations.

The key to construction safety risk management is to carry out a construction safety risk evaluation. With regards to high-pile wharf construction, the involved project-related parties, machinery and equipment, as well as the construction environment are extremely complex and highly linked in comparison with conventional civil construction, which is the most challenging aspect of its construction safety risk assessment. Currently, the methods used for the construction safety risk assessment of these projects mainly include some conventional methods such as professional scoring, the analytic hierarchy process, the entropy weight method, as well as some newly developed strategies including the fuzzy comprehensive evaluation method, the neural network method and so on. However, in specific engineering projects, no matter which kind of safety risk assessment method is adopted, it faces some difficulties, for example, how to determine the weights for specific indicators, how to represent the correlation between the indicators and their impact on different safety assessment indicators, etc. Therefore, it may not be sufficient to adopt only a single type of assessment method to carry out safety risk assessments in engineering construction, and it is necessary to have a comprehensive understanding of several safety risk assessment methods.

- (1) The professional scoring method refers to the use of professional work practices to assign values to different parameters that cannot be identified by an enterprise and analyze them, combining a number of professional points of view to arrive at a more intuitive result [6]. This approach is relatively simple and effective and is usually used in conjunction with other assessment tools in project design.
- (2) The analytic hierarchy process (AHP) is a network system weighting analysis method that integrates qualitative and quantitative considerations proposed by Saaty [40]. The core principle is that the research object is classified into several levels according to certain criteria, and each level of risk factors is identified based on expert assessments so as to find the factors that have the greatest impact on the research results. However, because the hierarchical analysis method is limited by the subjective judgment and professional ability of the researcher, it may also lead to the failure of the judgment of the project, so it is best to be applied together with other assessment tools.
- (3) The entropy weighting method is a way of assigning weights based on objective data, which is determined by the availability of data [41]. Entropy can be used as a measure of uncertainty, which is higher when data availability is low and lower when data availability is high. The entropy weighting method helps to extract valid information from the data set of multiple indicators and convert it into more accurate entropy values, thus obtaining more accurate indicator weights.
- (4) The fuzzy comprehensive evaluation (FCE) method can be utilized to identify complex objects with uncertainty [34]. By establishing the risk evaluation set and risk alternative set, constructing the factor weight set, the fuzzy relationship affiliation evaluation matrix, the single-factor fuzzy evaluation and the multi-factor fuzzy evaluation can be implemented, by which the comprehensive evaluation of assessment

indexes is realized. The fuzzy insinuating relationship degree technique can effectively convert complex qualitative problems into quantitative forms, and it can also effectively solve the systematic problems of multi-objective uncertain objects. The logic of FCE is clear and easy to operate, so it has been widely applied to various kinds of engineering projects.

- (5) Neural network analysis can be regarded as an accurate assessment tool [42], which can effectively capture and characterize complex information, which can be used to infer and predict future trends based on this information. This technique can help researchers to obtain information more accurately and quickly, so that they can develop assessments more objectively and accurately. Despite its good self-learning ability and resistance to failure, neural network analysis still faces great challenges. Limitations in the number of samples, quality and selection of regions make its results very unpredictable.

In this study, a so-called FAHP method, which synthesizes the FCE and AHP methods, is proposed to carry out the risk assessment of the construction of a high-pile wharf. In addition, the indicator weights are determined by the entropy weighting method. Moreover, the objectives are divided into several levels of recursive hierarchies based on the hierarchical analysis method, by which the interrelationships between the safety risk factors at each level can be clarified. On the other hand, the fuzzy evaluation method helps to express the unspecified specific risk objectives in the form of “belonging to some extent” which quantitatively describes the likelihood of each risk objective [32]. Overall, FAHP not only summarizes the valuable work experience of scholars but also can use fuzzy synthesis theory to solve the risk mapping relationship more appropriately, which reduces the subjectivity of experts’ judgment and thus promotes the quantification of the risk factor relationship. The specific practice of FAHP is to firstly establish the set of risk weights based on hierarchical analysis and then determine the risk weights of risk indicators by using Lagrangian weights [43]. The Lagrange median theorem is used to calculate the proportion of the two weights and the final weights are calculated. The affiliation degree of the alternative set is determined by the fuzzy comprehensive evaluation method, and then the fuzzy hierarchical comprehensive evaluation is carried out by establishing the single-factor and multi-factor hierarchical evaluation matrices with the principle of the maximum affiliation degree.

3. Methodology

3.1. Determination of Safety Risk Assessment Indicators

Most high-pile wharf constructions are offshore constructions, which are characterized by harsh construction conditions, high danger of cross-operation and great difficulty in organization and coordination. Especially, they are a great challenge for the cooperation and coordination of the construction work site because of the heavyweight and difficult lifting of the prefabricated components widely used in the project, which makes the component construction operation become the main source of frequent construction safety accidents. Therefore, accurately analyzing the safety risk factors according to the safety risk characteristics of the project and the actual construction safety management requirements of the specific project is a necessary precondition to ensure the safety of high-pile wharf construction and an important basis for subsequent construction safety management.

In fact, the safety risk analysis of high-pile wharves is complicated because of the variety of components and the uncertainty of the safety risk degree of the safety risk factors. Even worse, the numerous safety risk factors during the installation and construction of components are sometimes linked. Based on the case-based analysis of the construction safety accidents of high-pile wharves in China as well as national technical standards such as the Standard of Construction Safety Inspection (JGJ 59-2021) [44] and Technical Standard for Assembled Buildings with Concrete Structure (GB/T 51231-2016) [45], the primary causes of construction safety accidents of high-pile wharves are categorized and summa-

rized according to the five aspects of involved personnel, materials, facilities, management and environment, as shown in Table 1.

Table 1. Summary of the causes of construction safety accidents.

Accident Factors	Causes
Personnel	a. Safety awareness b. Technical level of on-site professional operation c. Emergency response capability and experience d. Physical fitness e. Safety production qualification f. Safety precautions g. Continuous working hours
Materials	a. Quality problem b. Transportation of materials or components c. Equipment overloading d. Stacking of materials or components e. Procurement and storage of materials or components f. Site acceptance of materials or components
Facilities	a. Safety protection of equipment b. Regular maintenance and maintenance of equipment c. Mechanical equipment safety inspection d. Cross-operation e. Hoisting equipment management f. Reliability checks and management of large equipment g. Construction equipment installation and removal control
Management	a. Site safety management system b. Overall construction arrangement c. Safety education and training d. Site safety inspection e. Supervision and implementation of emergency rescue system
Environment	a. Construction site environment b. Surrounding environment c. Natural adverse environment d. Working environment

Analyzing the 29 causes of high-pile wharf construction accidents, it can be seen that there are problems such as unspecific content and the relative redundancy of indicators, which will lead to smaller differences and inaccurate results in the target safety risk evaluation between different factors. Addressing these difficulties, the questionnaires were carefully designed and distributed to the relevant experts, whose characteristics are briefly listed in Table 2. Based on the experts' opinions and the actual situation of construction operations at the project site, the dominant safety risk factors of the high-pile wharf construction were specified and simplified.

Table 2. The characteristics of the experts.

Experts	Occupation	Position/Title	Experience (Year)	Education Level
1	Construction unit	Manager or engineer	>5	Bachelor or above
2	Construction control unit	Manager or engineer		
3	Design unit	Technical director or engineer		
4	Research institution and university	Professor or investigator		

With the aid of the accident causation theory and the existing research results on the safety risk of high-pile wharf constructions [5,14,46], the safety risk assessment indicators

of the project can be constructed, as shown in Figure 1. It should be pointed out that the gray correlation analysis method is used to simplify the above indicators [47]. Under the condition of ensuring that the classification ability remains unchanged, the indicators that cannot distinguish the results of the evaluation object data are filtered out. Gray correlation analysis has no special requirements for the sample distribution state and the number of samples, and its analysis and calculation of data can be completed through simple programming, eliminating the tedious calculation process. In addition, gray correlation analysis can ensure the accuracy of safety risk evaluations without losing effective information while filtering and deleting the redundant safety risk factors, which effectively reduces the time for the safety evaluation of the high-pile wharf construction process. Specifically, a hierarchical research structure is utilized to construct the indicator system, in which safety risk management for the construction of a high-pile wharf is taken as the target layer. The principle layer is composed of five aspects, namely, project personnel (A), materials (B), facilities (C), management (D) and environment (E). The specific evaluation indexes are included as the scheme layer, which contains indicator factors related to the actual projects. The specific evaluation indexes in the scheme layer are denoted as $A1, A2, B1, B2, \dots, E1, E2, E3$, which can be found in Figure 1.

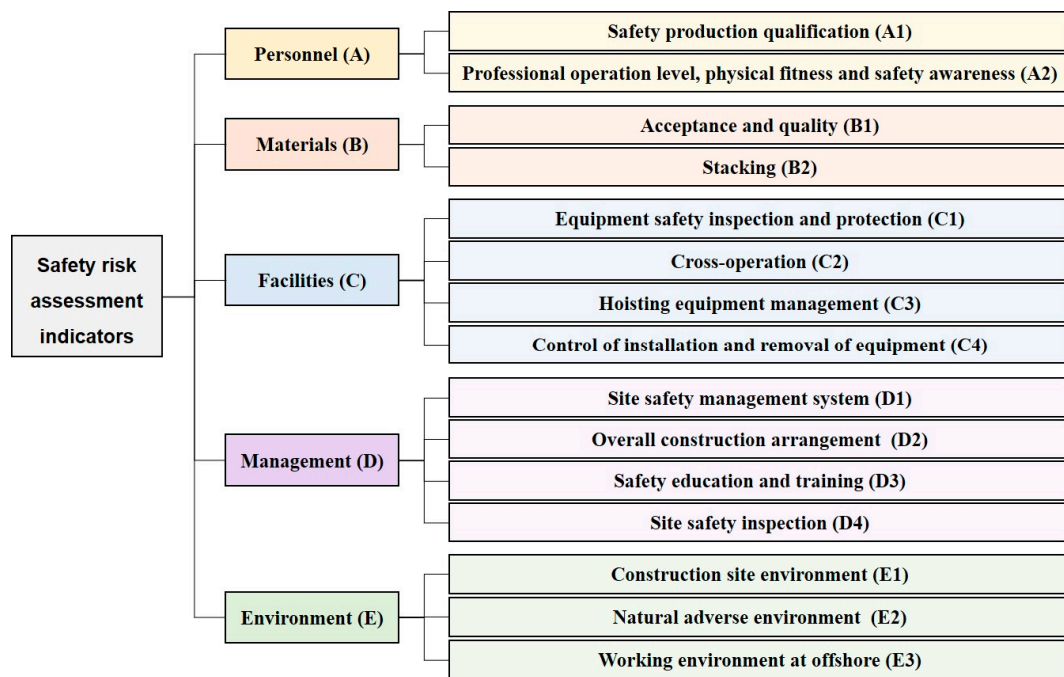


Figure 1. The improved and simplified hierarchical structure of the construction safety risk assessment indicators.

3.2. Construction Safety Risk Assessment Algorithm

In order to quantify the safety risk of the high-pile wharf construction, the safety risk assessment algorithms for each sub-process involved in the high-pile wharf construction were established based on the risk evaluation theory. The safety risk assessment indicators of the principle layer (i.e., construction personnel, materials, facilities, management and environment) determined above were represented by A, B, C, D and E, respectively. The safety risk assessment score was the multiplication result of the safety risk assessment score and the corresponding weight regarding the five indicators for each sub-process, and the score set of each sub-process is recorded as $\{f_1, f_2, \dots, f_i\}$, $i = 1, 2, \dots, P$, which can be expressed as

$$f_i = \sum_{j=1}^5 S_{ij}W_j, \quad (1)$$

where S_{ij} and W_j are the score value and weight of the j th risk indicator from A, B, C, D and E of the i th sub-process, $i = 1, 2, \dots, P$, $j = A, B, C, D$ and E and P is the total number of the sub-processes. It should be mentioned that the score value regarding each safety risk assessment indicator are normalized according to the score range before the summation operation so that the assessed scores are comparable between each sub-process and to facilitate further risk estimations. The score of five assessment indicators, S_A , S_B , S_C , S_D and S_E , are calculated by

$$S_A = A1 + A2 \quad (2)$$

$$S_B = B1 + B2 \quad (3)$$

$$S_C = c_1 \times C1 + c_2 \times C2 + c_3 \times C3 + c_4 \times C4 \quad (4)$$

$$S_D = d_1 \times D1 + d_2 \times D2 + d_3 \times D3 + d_4 \times D4 \quad (5)$$

$$S_E = E1 + E2 + E3 \quad (6)$$

and the calculation method of each parameter in the formula is shown in Table 3.

Table 3. Calculation methods of parameters in safety risk assessment indicators.

Assessment Indicator	Calculation Method
A1	This is determined by the results of the safety production qualification examination, with $A1 = 1 - \text{average score}/\text{total score}$.
A2	Refers to the age of participant and professional skill level certificate. $A2 = \sum \text{age} \times (1 - \text{average level}/\text{maximum level})/60$.
B1	$B1 = 1 - \text{pass rate of acceptance and sampling inspection}$.
B2	$B2 = 1 - (\text{categorizing and stacking in accordance with the layout plan [0.25]} + \text{with clear labeling of name, type, specification and quantity [0.25]} + \text{receiving and dispatching system [0.25]} + \text{person in charge of timely cleanup [0.25]})$. **
C1	$C1 = 1 - (\text{safety check score [0.6]} + \text{protection measures score [0.4]})$. **
C2	$C2 = \text{proportion of large equipment working at the same time on the project site}$.
C3	$C3 = \text{proportion of lifting equipment}$.
C4	$C4 = \text{identified installation and fixing areas [0.5]} + \text{specialized dismantling operators [0.5]}$. **
D1	$D1 = 1$ when there is no site safety management system; $D1 = 0.1$ when there is real-time site safety management system.
D2	$D2 = 0.6$ when the overall construction schedule is non-dynamic; $D2 = 0.2$ when the overall construction schedule is dynamically updated.
D3	$D3 = \text{frequency of security education and training}$.
D4	$D4 = \text{frequency of on-site safety inspections}$.
E1	$E1 = 1/\text{environment visibility index}$.
E2	$E2 = 1 - \text{actual construction days}/\text{estimated construction days}$.
E3	$E3 = 1$ when the construction is in open sea; $E3 = 0.3$ when the construction is in closed area.

** The numbers in the '[]' are the maximum score of the item, and the risk score can be determined according to the practical situation within 0~maximum score.

It is noted that the number of elements in the corresponding scheme layer for the five principle layers shown in Table 3 are not the same, which are 2, 2, 4, 4 and 3, respectively. Strictly speaking, the weights of each component in the scheme layer should vary depending on the contribution of the components to the corresponding principle layer. In order to ensure that the adopted weights can truly reflect the engineering situation, the safety risk questionnaires were designed and distributed to experts in the construction safety management of high-pile wharfs. According to several communications with the scoring experts, the assessment indicators were revised and improved to make them more

applicable to the actual situation of engineering construction safety assessments. Based on the results of the expert questionnaire survey, it was found that the weights of each element in the corresponding scheme layer containing no more than three elements (i.e., A, B and E) were basically equal and stable throughout the whole construction process. Therefore, as shown in Equations (2)–(6), the scores of the indicators A, B and E were directly summarized as the estimated score of the specific principle layer. For the remaining two elements in the principle layer, it was suggested that the element weights of C (i.e., c_1, c_2, c_3, c_4) and D (i.e., d_1, d_2, d_3, d_4) should be assigned specifically according to practical experience. Here, the classic Delphi method by sending a questionnaire was utilized to collect the weight of each element [32], which contained the four steps of questionnaire design, expert selection, data acquisition and data processing. The score matrix of the sub-processes in the high-pile wharf construction can be obtained by

$$(S_{ij})_{P \times 5} = \begin{bmatrix} S_{A1} & S_{B1} & S_{C1} & S_{D1} & S_{E1} \\ S_{A2} & S_{B2} & S_{C2} & S_{D2} & S_{E2} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ S_{AP} & S_{BP} & S_{CP} & S_{DP} & S_{EP} \end{bmatrix} \quad (7)$$

Then, a hierarchical analysis model was established to calculate the weights of the indicators for each sub-process. The judgment matrix of each risk assessment indicator was constructed using the 1–9 level X_{mn} scale method, as shown in Equation (8). X_{mn} expresses the relative importance of factors m and n . The factors in this paper were the above five risk assessment indicators A, B, C, D and E.

$$X_{mn} = \begin{bmatrix} X_{11} & X_{12} & X_{13} & X_{14} & X_{15} \\ X_{21} & X_{22} & X_{23} & X_{24} & X_{25} \\ X_{31} & X_{32} & X_{33} & X_{34} & X_{35} \\ X_{41} & X_{42} & X_{43} & X_{44} & X_{45} \\ X_{51} & X_{52} & X_{53} & X_{54} & X_{55} \end{bmatrix} \quad (8)$$

The indicator weight can be calculated based on the indicator weighting method as presented in Equations (9)–(11). It should be noted that the consistency was tested by comparing the maximum eigenvalue of the judgment matrix and the eigenvectors $W = [W_1, W_2, W_3, W_4, W_5]$ that met the consistency test, which were exactly the weight values of the corresponding risk indicators.

$$p_m = \prod_{n=1}^5 X_{mn} \quad (9)$$

$$\omega_m = \sqrt[5]{p_m} \quad (10)$$

$$W_m = \omega_m / \sum_{m=1}^5 \omega_m \quad (11)$$

4. Results and Discussion

4.1. Project Overview and Construction Analysis

The project envisages the construction of four general-purpose berths with 50,000 to 150,000 tons, which will be used primarily for the transportation of minerals, steel and other general cargo. The wharf type is a high-pile wharf, and the construction mainly consists of three parts: wharf, approach bridge and ancillary facilities. The project adopts a high-pile girder slab structure, and prefabricated girders are mostly used in the construction. Moreover, the panels are a stacked combination of prefabricated panels and cast-in-place panels. Considering the difficulties in the offshore construction of high-pile wharves, the construction safety challenges of this project mainly lie in the following three points:

- (1) Restricted island operation and difficult resource organization: the project is an isolated island operation in the outer sea, which makes the transportation of materials and equipment difficult, and there is sea fog in spring, typhoons in summer and frequent cold air in winter, which reduces the actual number of days available for

operation. The project schedule is of a high intensity and busy. A large number of resources, engineers, ships and machines and transport vehicles are invested in during the peak period, which makes the project organization difficult and puts forward very high requirements on the project safety construction.

- (2) Poor construction conditions and less effective operating time: the project construction area involves open sea, poor construction conditions. Wind and waves have a great impact on the safety of construction operations, and especially, the impact of long periods of surging waves cannot be ignored, and the project's construction safety risks caused by the winter cold wave and summer tropical cyclones have a greater impact.
- (3) Work surface cross-operation, organization and coordination difficulties: the number of construction wharves, wharves and wharves net distance is small and close to the embankment, the workspace is crowded, the construction operation of the ship and machine interfere with each other and there is a cross-construction caused by the construction safety risk potential hazards.

As shown in Figure 2, the construction process of the project consists of three major parts, namely, the wharf construction, approach bridge construction and other facilities installation. Among them, according to the components and construction methods involved, the construction of the wharf includes five divisions: steel pipe pile sinking, cast-in-place lower crossbeam construction, longitudinal and transverse beam installation, cast-in-place upper crossbeam construction and panel installation. The construction of the approach bridge includes four divisions: steel pipe pile, steel-sheath immersed pile sinking, embedded rock piles construction, cast-in-place approach piers construction and hollow core slab installation. Moreover, the construction of other facilities includes cast-in-place joints and surfacing construction and ancillary facilities installation.

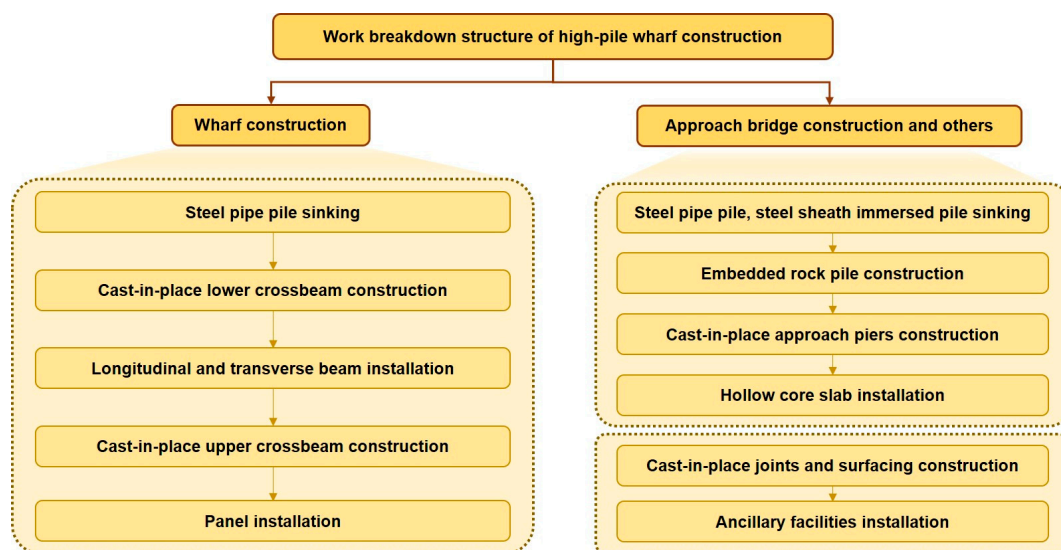


Figure 2. The work breakdown structure of high-pile wharf construction.

4.2. BIM Model for Safety Risk Management of High-Pile Wharf Construction

The Autodesk Revit 2020 software was mainly used to establish the model of the high-pile wharf, for which the BIM model and the important construction process are shown in Figure 3. Firstly, a common component family library of the high-pile wharf was established, by which the 3D modelling of the wharf including the dock main body, ancillary facilities and the surrounding scene could be performed quickly and accurately. With the help of the BIM model, the details and corresponding physical and functional properties of each component involved in the wharf not only could be visualized and statistically analyzed, but it also helped to understand the design intent. Importantly, the property parameters of each component in the model not only contained basic parameters such as geometry,

material, cost and construction duration but also involved the construction safety risk parameters of the high-pile wharf after the analysis of construction safety risk indicators for high-pile wharves. These attributes contained the basic parameters of safety risk assessments and further calculation for each individual component, such as the construction mode, cross-construction index, bad weather index, etc., which supplied the detailed data for the subsequent construction safety risk analysis and information management.

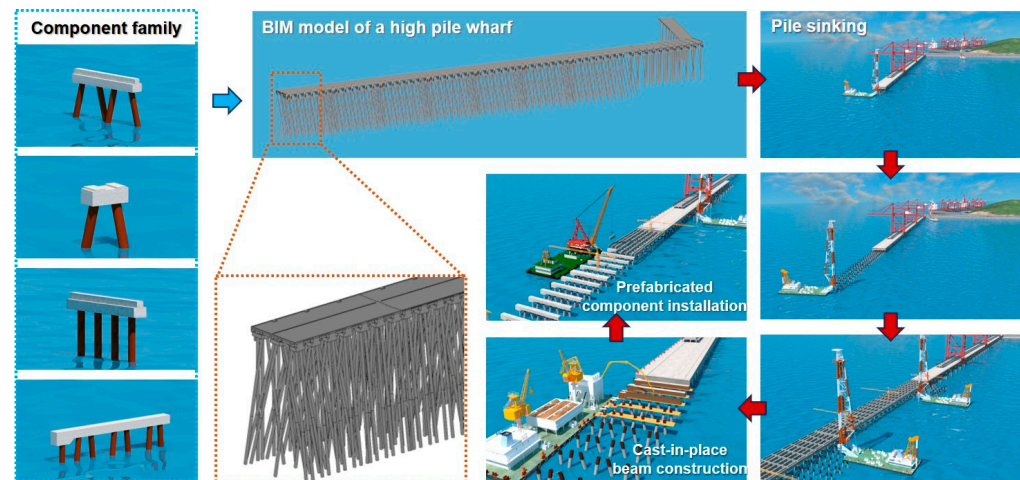


Figure 3. BIM model and some of the typical construction process of high-pile wharf.

4.3. Safety Risk Assessment of the High-Pile Wharf Construction

Based on the safety risk assessment algorithm established above, the safety risk analysis of the construction of this high-pile wharf can be carried out. Theoretically, for each sub-process shown in Figure 2, there are 15 corresponding risk indicators, as shown in Figure 1. However, the value and calculation of these indicators for each sub-process may be different. For example, hoisting equipment is mainly used in the pile-sinking construction process, so its corresponding safety risk score C3 will be very high. In contrast, construction site management and safety construction in cast-in-place concrete construction are more important, so its corresponding score of A1, A2, D1, D2 and D3 will be relatively larger. In order to objectively and accurately give the safety risk indicators of these sub-processes, the affiliation theory of fuzzy mathematics is employed to quantitatively evaluate the five first-level indicators (principle layer) and 15 s-level assessment indicators (scheme layer) involved in this high-pile wharf project. By calculating the affiliation degree of each index, its corresponding comprehensive evaluation matrix is obtained. Combined with the weights of the above indicators, the fuzzy comprehensive evaluation results of each indicator in both the principle layer and scheme layer can be calculated. Accordingly, the fuzzy comprehensive evaluation matrix is established, and the component safety risk parameters A1, ..., E3 involved in each sub-process are attached to the BIM model of each component as a component parameter. Taking the steel pipe pile sinking pile construction in the wharf construction as an example, the calculation process of the relevant parameters is briefly described.

4.3.1. Determination of Indicator Weights

First of all, the expert discrimination matrix survey table was established, and the evaluation matrix for the five indicators in the principle layer was established as follows:

$$X_{mn} = \begin{bmatrix} 1 & 2 & 3 & 3 & 4 \\ 1/2 & 1 & 5 & 2 & 4 \\ 1/3 & 1/5 & 1 & 2 & 3 \\ 1/3 & 1/2 & 1/2 & 1 & 2 \\ 1/4 & 1/4 & 1/3 & 1/2 & 1 \end{bmatrix} \quad (12)$$

This led to the corresponding weights of the four indicators at the principle level being evaluated as $W = [W_1, W_2, W_3, W_4, W_5] = [0.3863, 0.2990, 0.1339, 0.1148, 0.0659]$. The consistency test parameters were $\lambda_{max} = 5.3003$, $CI = 0.075$, $CR = 0.0670$, where λ_{max} was the maximum eigenvalue, random consistency index and consistency ratio of the judgment matrix X_{mm} .

4.3.2. Safety Risk Score Calculation

For the steel pipe pile-sinking construction, the calculation of the safety risk score regarding the five assessment indicators was implemented based on Equations (2)–(6) and Table 3. Specifically, the safety risk questionnaires were distributed to 30 experts in engineering facilities and management. Based on the final 28 questionnaires recovered, the weights in Equations (4) and (5) could be calculated. The calculation of the five safety indicators S_A , S_B , S_C , S_D and S_E for the sub-process of steel pipe pile sinking is shown below:

- (1) S_A : Before the construction of the project, a safety production qualification examination was carried out for the operators of the pile-sinking construction. The total score of the question paper was 100, the number of participants was 20 and the average score was 72.5, which gave $A1 = 0.275$. According to the age of the operators of the pile-sinking construction and the level of their professional skill certificate, it was obtained that $A2 = 0.4911$. Therefore, $S_A = A1 + A2 = 0.7661$.
- (2) S_B : It was found that the materials to be used in the construction of steel pipe piles included not only the prefabricated piles themselves but also ~15 kinds of materials such as iron parts, steel wire ropes, welding rods, concrete and reinforcing bars. The pass rate of acceptance and sampling inspection of each material was recorded and averaged to get $B1 = 0.1164$. Examining the stockpile sites and stockpile management practices for 16 kinds of materials yielded $B2 = 0.35$. $S_B = B1 + B2 = 0.4664$.
- (3) S_C : Based on the statistical results of the questionnaire, the weights of the four elements of the scheme layer were $\{0.15, 0.35, 0.3, 0.2\}$. By recording the frequency of safety checks and the protection measures taken, $C1 = 0.2$. According to the construction information, the pile sinking involved the crossover of 15 types of large-scale machinery, including piling vessels, motorized boats, marine piling hammers, cranes, forklifts and so on. The installation areas were generally identified and the dismantling operators were satisfied. Therefore, $C2 = 0.6$, $C3 = 0.2$ and $C4 = 0.1$. $S_C = 0.32$.
- (4) S_D : Based on the statistical results of the questionnaire, the weights of the four elements of the scheme layer were $\{0.25, 0.2, 0.25, 0.3\}$. According to the project management system and site situation, $D1 = 0.3$, $D2 = 0.4$, $D3 = 0.25$ and $D4 = 0.05$. $S_D = 0.23$.
- (5) S_E : According to the recorded visibility index for one year, the number of actual construction days, it was calculated that $E1 = 0.125$ and $E2 = 0.11$. The construction was located at open sea, $E3 = 0.3$. $S_E = E1 + E2 + E3 = 0.535$.

Based on the above-mentioned procedure, the safety risk assessment data of 11 sub-processes of this high-pile wharf project could be calculated. The safety risk scores for all the sub-processes could be calculated based on Equation (1), which were

$$\{f_1, f_2, \dots, f_i\} = \{0.54, 0.39, 0.33, 0.37, 0.31, 0.61, 0.53, 0.39, 0.31, 0.35, 0.06\},$$

as shown in Figure 4. It can be found that the construction risk assessment value of each sub-process can be visualized and quantitatively analyzed by specific values. Among them, the safety risk score of pile construction is higher in the construction of the wharf and approach bridge; cast-in-place beams, cast-in-place joints and surfaces and cast-in-place piers are second; and the safety risk score of the construction of ancillary facilities is the smallest. However, for the project site construction and management personnel, further comparison and analysis of the values and their correspondence to each process will still

bring a large amount of workload, which is not inherent and also affects the communication and collaboration between different departments. Especially in case of an emergency, it will also affect the efficiency of emergency response and decision-making time. It is of great significance to establish a visualized platform that is capable of presenting the safety risk information at all levels of the project according to the requirements from a variety of stakeholders in the project.

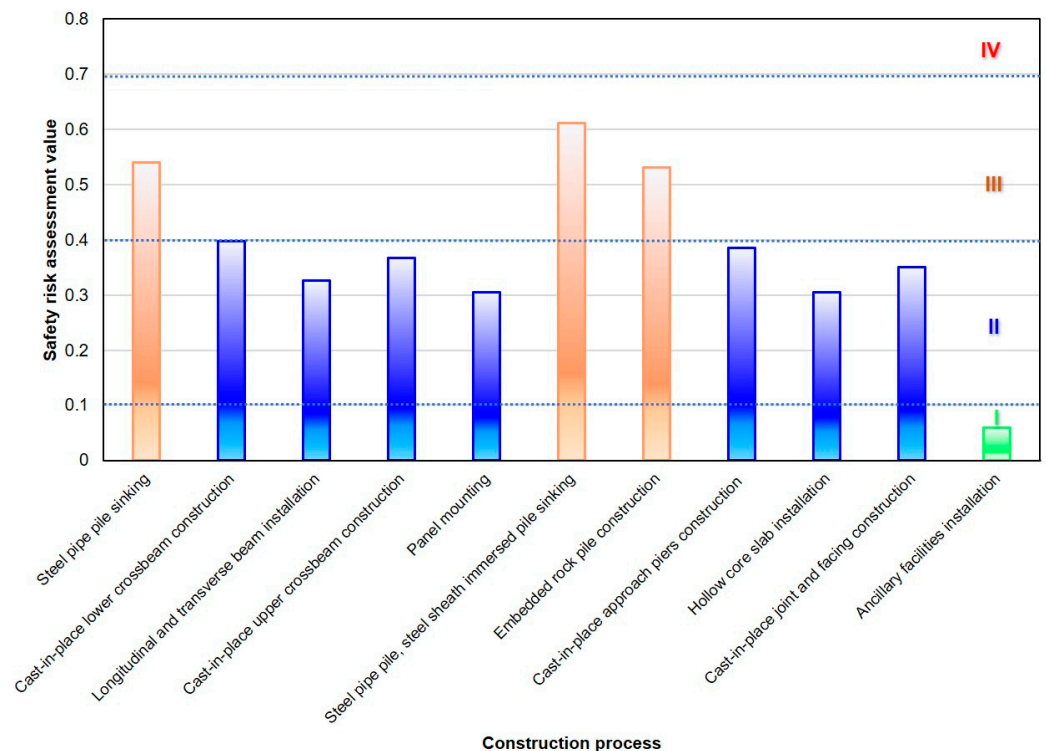


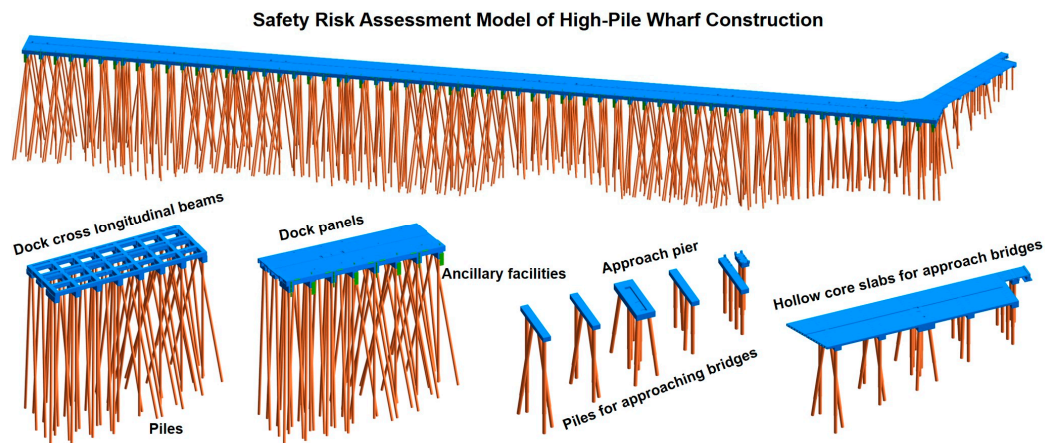
Figure 4. The safety risk levels of each sub-process.

4.4. BIM-Based Safety Risk Evaluation Platform

In order to facilitate the identification and categorization management of project construction-related personnel, this project referred to the safety level classification method of highway and water transportation risk assessments and divided the above risk assessment scores into four levels according to Table 4, corresponding to light risk, medium risk, higher risk and high risk. On this basis, the safety risk level of each sub-process was determined according to Table 4, by which the safety risk level in BIM could be identified by colors through the establishment of a visualized model of the safety risk level for each component of the high-pile wharf, as shown in Figure 5. This method realized the real-time tracking of the safety risk assessment data based on the 3D visualization model of the project. On one hand, it simplified the data analysis and calculation work of the project management personnel. On the other hand, it provided real-time, accurate, organized and visualized safety risk assessment results for the stakeholders in the project. For example, once the red safety assessment data appeared in the model, the system could give early warning information immediately, and the project-related personnel could send early warnings and take emergency response measures for the first time. The quantitative and visualized information provided by the BIM platform is conducive for the safety management personnel to control the whole situation and provides guidance to analyze the causes of some safety accidents, which improves the effectiveness and pertinence of the wharf safety control measures.

Table 4. Classification of safety risk of high-pile wharf construction.

Risk Level	Range	Color
I	$f \leq 0.1$	Green
II	$0.1 < f \leq 0.4$	Blue
III	$0.4 < f \leq 0.7$	Orange
IV	$0.7 < f \leq 1$	Red

**Figure 5.** Classification of safety risk evaluation.

Furthermore, it can be found in Figure 5 that the construction safety risk assessment of the steel pipe pile-sinking construction of the wharves and approach bridges in this project is presented as orange color, which implies a higher risk. Reviewing the scores of the safety risk assessment indicators for pile foundation construction in detail, the scores given by S_B and S_C were significantly higher than those of other sub-processes, which mainly related to the large scale of the pile foundation project. In fact, a large amount of pile foundation constituent materials and large-scale machinery and equipment were utilized in the construction process of those sub-processes, and thus the corresponding construction safety risk levels were higher. This inspired managers to develop improvement measures based on the assessment data, such as reducing the number of large machinery and equipment with repetitive functions, adopting multifunctional construction machinery or carrying out construction simulations based on the BIM platform to streamline and optimize the construction process of pile sinking and the types of materials required to reduce the potential construction safety risks.

5. Conclusions

In this paper, a visualized digital construction safety risk assessment system for high-pile wharf construction was established by the combination of safety risk assessment theory and BIM technology. The safety risk indicators of high-pile wharf construction were determined based on the proposed FAHP method which was the integration of the fuzzy comprehensive evaluation and analytic hierarchy process methods. In this way, the construction safety risk scores of each sub-process in the high-pile wharf project were quantitatively calculated, and the corresponding safety risk levels were accordingly clarified. The following conclusions can be drawn:

- (1) The construction safety risk assessment system contains physical parameters and safety risk indicators of each component, which can be used for safety risk assessments and visualization management during the construction of the high-pile wharf, providing a database, visualization analysis and management platform for the safety risk assessment of the high-pile wharf.
- (2) The accurate identification and categorization of construction safety risk factors are important prerequisites for safety risk assessment in high-pile wharf construction.

The construction risk assessment system based on hierarchical analysis proposed in this paper was constructed by the target layer, principle layer and scheme layer. The construction risk assessment of the high-pile wharf was taken as the target layer, and the five main influencing factors affecting the construction risk were the principle layer, which included personnel, materials, facilities, management and environment. Consequently, there were 15 elements in the scheme layer.

- (3) The safety risk score calculated by the FAHP method could indicate the construction risk of each sub-process in the high-pile wharf. The level of safety risk could be directly presented in the BIM platform and changed with the actual situation of the construction site, which helped the project management personnel to realize the project safety risk in real time and give a timely response to the risk warning signal given by the BIM safety risk management system.
- (4) It should be pointed out that the weights of some risk indicators for management and the facility in the principle layer were obtained by the Delphi method, which subjectively relied more on the expert's professional knowledge and experience and might affect the estimated weights. As a future work, it was suggested that some advanced estimation methods can be further employed in the proposed safety risk assessment method for a more objective and accurate estimation of the risk indicator weights.

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References

- Li, M.; Ren, Q.; Li, M.; Kong, T.; Li, H.; Tian, H.; Liu, S. Digital Twin-Enabled Collision Early Warning System for Marine Piling: Application to a Wharf Project in China. *Adv. Eng. Inform.* **2024**, *59*, 102269. [\[CrossRef\]](#)
- Su, J.-B.; Yang, G.-Q.; Zhang, L.-M.; Shao, G.-J.; Zhu, R.-H. Safety Evaluation Method for High-Piled Wharf Structures Based on the Disturbing-Energy Method. *J. Eng. Mech.* **2020**, *146*, 04020044. [\[CrossRef\]](#)
- Makarova, I.; Buyvol, P.; Mukhametdinov, E.; Boyko, A. The Construction of Seaports in the Arctic: Prospects and Environmental Consequences. *J. Mar. Sci. Eng.* **2023**, *11*, 1902. [\[CrossRef\]](#)
- Li, Z.; Ramirez, C.R. Design and Construction of the Texaco Wharf Maritime Port Facility, Puerto Cortés, Honduras. *PCI J.* **2002**, *47*, 78–88. [\[CrossRef\]](#)
- Alarcón, L.F.; Acuña, D.; Diethelm, S.; Pellicer, E. Strategies for Improving Safety Performance in Construction Firms. *Accid. Anal. Prev.* **2016**, *94*, 107–118. [\[CrossRef\]](#)
- Awolusi, I.G.; Marks, E.D. Safety Activity Analysis Framework to Evaluate Safety Performance in Construction. *J. Constr. Eng. Manag.* **2017**, *143*, 05016022. [\[CrossRef\]](#)
- Grabowski, M.; Ayyalasomayajula, P.; Merrick, J.; Harrauld, J.R.; Roberts, K. Leading Indicators of Safety in Virtual Organizations. *Saf. Sci.* **2007**, *45*, 1013–1043. [\[CrossRef\]](#)
- Schmitz, P.; Reniers, G.; Swuste, P.; van Nunen, K. Predicting Major Hazard Accidents in the Process Industry Based on Organizational Factors: A Practical, Qualitative Approach. *Process Saf. Environ.* **2021**, *148*, 1268–1278. [\[CrossRef\]](#)
- Choudhry, R.M.; Fang, D.; Mohamed, S. The Nature of Safety Culture: A Survey of the State-of-the-Art. *Saf. Sci.* **2007**, *45*, 993–1012. [\[CrossRef\]](#)
- Hallowell, M.R.; Hinze, J.W.; Baud, K.C.; Wehle, A. Proactive Construction Safety Control: Measuring, Monitoring, and Responding to Safety Leading Indicators. *J. Constr. Eng. Manag.* **2013**, *139*, 04013010. [\[CrossRef\]](#)
- Gunduz, M.; Laitinen, H. Construction Safety Risk Assessment with Introduced Control Levels. *J. Civ. Eng. Manag.* **2018**, *24*, 11–18. [\[CrossRef\]](#)
- Zhou, W.; Whyte, J.; Sacks, R. Construction Safety and Digital Design: A Review. *Automat. Constr.* **2012**, *22*, 102–111. [\[CrossRef\]](#)

13. Wang, S.; Yin, J.; Khan, R.U. Dynamic Safety Assessment and Enhancement of Port Operational Infrastructure Systems during the COVID-19 Era. *J. Mar. Sci. Eng.* **2023**, *11*, 1008. [\[CrossRef\]](#)
14. Liu, Z.; Meng, X.; Xing, Z.; Jiang, A. Digital Twin-Based Safety Risk Coupling of Prefabricated Building Hoisting. *Sensors* **2021**, *21*, 3583. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Li, J.; Wang, Y.; Wang, X.; Luo, H.; Kang, S.-C.; Wang, J.; Guo, J.; Jiao, Y. Benefits of Building Information Modelling in the Project Lifecycle: Construction Projects in Asia. *Int. J. Adv. Robot. Syst.* **2014**, *11*, 124. [\[CrossRef\]](#)
16. Hatmoko, J.U.D.; Fundra, Y.; Wibowo, M.A. Zhabrinna Investigating Building Information Modelling (BIM) Adoption in Indonesia Construction Industry. *MATEC Web Conf.* **2019**, *258*, 02006. [\[CrossRef\]](#)
17. Zubair, M.U.; Ali, M.; Khan, M.A.; Khan, A.; Hassan, M.U.; Tanoli, W.A. BIM- and GIS-Based Life-Cycle-Assessment Framework for Enhancing Eco Efficiency and Sustainability in the Construction Sector. *Buildings* **2024**, *14*, 360. [\[CrossRef\]](#)
18. Sriyolaja, Z.; Harwin, N.; Yahya, K. Barriers to Implement Building Information Modeling (BIM) in Construction Industry: A Critical Review. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *738*, 012021. [\[CrossRef\]](#)
19. Ullah, K.; Lill, I.; Witt, E. An Overview of BIM Adoption in the Construction Industry: Benefits and Barriers. In *Emerald Reach Proceedings Series*; Lill, I., Witt, E., Eds.; Emerald Publishing Limited: Bingley, UK, 2019; pp. 297–303. ISBN 978-1-83867-051-1.
20. Prabhakaran, A.; Mahamadu, A.-M.; Mahdjoubi, L.; Andric, J.; Manu, P.; Mzyece, D. An Investigation into Macro BIM Maturity and Its Impacts: A Comparison of Qatar and the United Kingdom. *Archit. Eng. Des. Manag.* **2021**, *17*, 496–515. [\[CrossRef\]](#)
21. Liu, Y.; Deng, Y.; Liu, Z.; Osmani, M. Integration of Building Information Modeling (BIM) with Transportation and Facilities: Recent Applications and Future Perspectives. *Buildings* **2024**, *14*, 541. [\[CrossRef\]](#)
22. Shim, J.-H.; Ham, N.-H.; Kim, J.-J. Collaborative BIM-Based Construction Coordination Progress Modeling Using Extended Collaborative Process Modeling (exCPM). *Buildings* **2024**, *14*, 358. [\[CrossRef\]](#)
23. Abanda, F.H.; Vidalakis, C.; Oti, A.H.; Tah, J.H.M. A Critical Analysis of Building Information Modelling Systems Used in Construction Projects. *Adv. Eng. Softw.* **2015**, *90*, 183–201. [\[CrossRef\]](#)
24. Bui, N.; Merschbrock, C.; Munkvold, B.E. A Review of Building Information Modelling for Construction in Developing Countries. *Procedia Eng.* **2016**, *164*, 487–494. [\[CrossRef\]](#)
25. Rozita, S.; Ehsan, S. Benefits of Implementing Building Information Modeling (BIM) in Infrastructure Projects. *J. Eng. Pro. Product. Manag.* **2020**, *10*, 123–140. [\[CrossRef\]](#)
26. Collinge, W.H.; Osorio-Sandoval, C. Deploying a Building Information Modelling (BIM)-Based Construction Safety Risk Library for Industry: Lessons Learned and Future Directions. *Buildings* **2024**, *14*, 500. [\[CrossRef\]](#)
27. Darwish, A.M.; Tantawy, M.M.; Elbeltagi, E. Critical Success Factors for BIM Implementation in Construction Projects. *Saudi J. Civ. Eng.* **2020**, *4*, 180–191. [\[CrossRef\]](#)
28. Usukhbayar, R.; Choi, J. Critical Safety Factors Influencing on the Safety Performance of Construction Projects in Mongolia. *J. Asian. Archit. Build.* **2020**, *19*, 600–612. [\[CrossRef\]](#)
29. Okakpu, A.; Ghaffarianhoseini, A.; Tookey, J.; Haar, J.; Ghaffarianhoseini, A.; Rehman, A.U. Risk Factors That Influence Adoption of Building Information Modelling (BIM) for Refurbishment of Complex Building Projects: Stakeholders Perceptions. *Int. J. Constr. Manag.* **2022**, *22*, 2446–2458. [\[CrossRef\]](#)
30. Park, J.; Lee, H.; Kim, H.Y. Risk Factor Recognition for Automatic Safety Management in Construction Sites Using Fast Deep Convolutional Neural Networks. *Appl. Sci.* **2022**, *12*, 694. [\[CrossRef\]](#)
31. Li, M.; Yu, H.; Jin, H.; Liu, P. Methodologies of Safety Risk Control for China's Metro Construction Based on BIM. *Saf. Sci.* **2018**, *110*, 418–426. [\[CrossRef\]](#)
32. Li, L.; Li, R.; Zhi, M.; Wang, S.; Cao, L. Risk Assessment of Building Foundation Pit Construction Based on Fuzzy Hierarchical Comprehensive Evaluation Method. *Geofluids* **2022**, *2022*, 9317700. [\[CrossRef\]](#)
33. Zhu, H.; Wang, Y. Intelligent Prediction of Prestressed Steel Structure Construction Safety Based on BP Neural Network. *Appl. Sci.* **2022**, *12*, 1442. [\[CrossRef\]](#)
34. Li, X.K.; Wang, X.M.; Lei, L. The Application of an ANP-Fuzzy Comprehensive Evaluation Model to Assess Lean Construction Management Performance. *Eng. Constr. Archit. Manag.* **2019**, *27*, 356–384. [\[CrossRef\]](#)
35. Chen, W.T.; Tsai, I.-C.; Merrett, H.C.; Lu, S.T.; Lee, Y.-I.; You, J.-K.; Mortis, L. Construction Safety Success Factors: A Taiwanese Case Study. *Sustainability* **2020**, *12*, 6326. [\[CrossRef\]](#)
36. Tixier, A.J.-P.; Hallowell, M.R.; Rajagopalan, B. Construction Safety Risk Modeling and Simulation. *Risk Anal.* **2017**, *37*, 1917–1935. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Yang, Q.; Yan, X.; Chen, W.; Fan, J. Construction and Application of Safety Management Scenarios at Construction Sites. *Appl. Sci.* **2024**, *14*, 404. [\[CrossRef\]](#)
38. Peng, G.; Han, L.; Liu, Z.; Guo, Y.; Yan, J.; Jia, X. An Application of Fuzzy Analytic Hierarchy Process in Risk Evaluation Model. *Front. Psychol.* **2021**, *12*, 715003. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Mahad, N.F.; Yusof, N.; Ismail, N.F. The Application of Fuzzy Analytic Hierarchy Process (FAHP) Approach to Solve Multi-Criteria Decision Making (MCDM) Problems. *J. Phys. Conf. Ser.* **2019**, *1358*, 012081. [\[CrossRef\]](#)
40. Saaty, T.L. Modeling Unstructured Decision Problems -the Theory of Analytical Hierarchies. *Math. Comput. Simulat.* **1978**, *20*, 147–158. [\[CrossRef\]](#)
41. Liu, F.; Zhao, S.; Weng, M.; Liu, Y. Fire Risk Assessment for Large-Scale Commercial Buildings Based on Structure Entropy Weight Method. *Saf. Sci.* **2017**, *94*, 26–40. [\[CrossRef\]](#)

42. Bala Murugan, S.; Lenin Sundar, M. Investigate Safety and Quality Performance at Construction Site Using Artificial Neural Network. *J. Intell. Fuzzy Syst.* **2017**, *33*, 2211–2222. [[CrossRef](#)]
43. Loron, A.S.; Loron, M.S.; Peyvandi, G. An Integrated Fuzzy Analytical Hierarchy Process-Fuzzy Data Envelopment Analysis Method for Intelligent Building Assessment. *Teh. Vjesn.* **2015**, *22*, 383–389. [[CrossRef](#)]
44. *JGJ 59-2011*; Standard of Construction Safety Inspection. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2011.
45. *GB/T 51231-2016*; Technical Standard for Assembled Buildings with Concrete Structure. Ministry of Housing and Urban-Rural Development of the People's Republic of China (MOHURD): Beijing, China, 2016.
46. Collinge, W.H.; Farghaly, K.; Mosleh, M.H.; Manu, P.; Cheung, C.M.; Osorio-Sandoval, C.A. BIM-Based Construction Safety Risk Library. *Automat. Constr.* **2022**, *141*, 104391. [[CrossRef](#)]
47. Li, H.; Chen, D.; Arzaghi, E.; Abbassi, R.; Xu, B.; Patelli, E.; Tolo, S. Safety Assessment of Hydro-Generating Units Using Experiments and Grey-Entropy Correlation Analysis. *Energy* **2018**, *165*, 222–234. [[CrossRef](#)]

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