Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 01, January, 2025

Safety Risk Assessment Model for Bridge Construction

Widi Hartono [1*], Stefanus A. Kristiawan [1], Dewi Handayani [1], Wahyudi Sutopo [2]

[1] *Department of Civil Engineering, Faculty of Engineering, Universitas Sebelas Maret, Ir. Sutami St. 36A, Surakarta 57126, Indonesia.*

[2] *Department of Industrial Engineering, Faculty of Engineering, Universitas Sebelas Maret, Ir. Sutami St. 36A, Surakarta 57126, Indonesia.*

Received 16 October 2024; Revised 03 December 2024; Accepted 11 December 2024; Published 01 January 2025

Abstract

In Indonesia, construction accidents have occurred during the construction of bridges and elevated roads, peaking in 2017. The lifting of girder beams has failed in several construction projects, and the formwork has failed during pier construction. The reasons for these work accidents are human and equipment factors, which caused material losses and loss of life. A risk assessment model for bridge construction work accidents in construction projects is proposed in this paper, with the work breakdown structure (WBS), risk breakdown structure (RBS), analytic hierarchy process (AHP), and rating being integrated to assess the risk of bridge construction work accidents. This model is expected to improve safety in bridge construction by providing effective safety planning, especially in the accident risk assessment process. The study results indicate that the WBS and RBS can outline and explain the identification of construction safety risks for bridges and provide insight into the interrelationship of construction phases and the potential risks. The relationship between the WBS and RBS is created in the form of a coupling matrix, and we identify the potential risky activities at each phase and the corresponding construction phases. The AHP can be used to calculate the weights and priorities of the WBS and analyze the magnitude of the risk index for its related risky activities; then, the rating method can be used to analyze the risk index. Girder and diaphragm installation work involves a high risk of workers falling during the erection of girders.

Keywords: Safety Risk; Bridge Construction; Work Breakdown Structure (WBS); Risk Breakdown Structure (RBS); Analytic Hierarchy Process (AHP); Rating.

1. Introduction

Accidents at the workplace in road and bridge construction projects in Indonesia are still a major issue that cannot be overlooked; the Indonesian government has not yet taken serious action to solve the problem. In 2017, the rate of work-related accidents in bridge construction was the highest, and many projects experienced accidents that killed materials and humans. In East Indonesia, the construction business is one of the most hazardous businesses in terms of workplace accidents, causing fatalities every year. Quantitative research using multiple linear analysis has revealed that 31 predictive factors are associated with occupational accidents, and 13 cost factors are derived from them with high probability factors [1].

The government of Indonesia continues to construct roads and bridges, especially in the eastern part of the country; management has remained quite ignorant of the negative impact on workplace safety. This, I believe, goes hand in hand with the notion that developmental activities do not always correspond with the implementation of safety measures at the occupational level. In addition, it was concluded that the main reason for accidents was the lack of understanding of the management staff as to the need to implement safety measures, especially in connection with the lifting of objects to the height of the buildings [2].

* Corresponding author: wieds_ts@ft.uns.ac.id

http://dx.doi.org/10.28991/CEJ-2025-011-01-010

Risk factors in bridge construction are many and require comprehensive risk control measures. Bridge construction involves various risks that need to be assessed and monitored systematically and rationally as a way of improving construction safety [3]. Safety issues are affected by a variety of factors, including human errors, equipment failures, management flaws, and environmental constraints [4]. Scientific and reasonable safety assessment and monitoring measures of bridge construction to enhance construction safety and reduce construction risks [3]. The bridge construction safety issues are multidimensional, which include poor working conditions, lack of use of personal protective equipment (PPE), lack of training and awareness, absence of safety plan, and unsafe practices in different construction activities [5]. Safety risk assessment is fuzzy and random, which makes it difficult for us to conduct construction safety assessment with an accurate degree. Bridge construction accidents can be fatal, resulting in serious property damage and casualties [6]. Construction of a toll road requires a holistic strategy to mitigate safety and security problems when lifting girders [7]; several safety issues have been developed in relation to these technologies and strategies.

A tool used for decomposition of a project into low segments of manageable size is the Work Breakdown Structure (WBS), which helps the identification of risks at the different stages of project development. The Work Breakdown Structure (WBS) helps projects organize; however, they are not always aligned with risk detection procedures. Work Breakdown Structure (WBS) can detect risks, but its direct relation with improving safety performance has yet to be fully studied [8, 9]. Its design is to run (with) WBS, yet at times there is disparity between the two structures. Without a unified framework that integrates RBS and WBS, the combined effectiveness of the two approaches to mitigate safety risk broadly [10] is constrained. The preceding is a significant deficiency in the irregular detection and evaluation of hazardous conditions during construction projects at diverse stages. It is widely believed that hazards should be detected at a pre-construction or design stage, and yet this is rarely done consistently. It has been suggested that a Work Breakdown Structure (WBS) can be used to detect risks during the design phase, yet the link between this and improving performance in safety remains poorly understood [8]. To fill this gap, this study provides a methodology for evaluating and analyzing the safety risk involved in the concrete bridge building process based on the WBS, RBS, AHP, and rating methods. To ensure safety compliance in infrastructure projects, this problem demands a huge effort from all stakeholders [2]. On this basis, the study makes four recommendations based on which tragic occurrences in road and bridge construction in eastern Indonesia can be prevented and safety standards improved within the construction industry [1]. Therefore, the more people that are aware, know, and are committed to occupational safety, the fewer accidents in the Indonesian bridge construction industry.

2. Literature Review

A large percentage of workplace accidents occur in the construction industry. It is reported that this business employs almost one third of the industrial workforce, and yet it accounts for more than 40% of all workplace fatalities [11]. The risks associated with work accidents that often occur in construction projects include exposure to falling from a height, exposure to being hit by materials and equipment falling from above head height, exposure to being pinched in equipment at the work site, exposure to an electric shock at the work site, and exposure to slipping at the work site [12]. Working at great heights, maneuvering heavy equipment, and working with hazardous substances are all part and parcel of construction labor, the inherent characteristics of which thus make the accident rates higher [11]. Despite the awareness of the perilous working conditions within the construction sector, including the risks of falling, electrocution, being struck by an object, being in accidents related to equipment, and exposure to hazardous chemicals [11, 13], a number of these hazards kill or injure a large number of people each year [14, 15]. The proper management of safety in excavation projects will prevent the environmental impacts and financial loss associated with project delay or failure [16]. The use of efficient safety measures may drastically decrease the cost of accidents in the workplace, such as costs related to medical expenses, compensation claims, and legal fees [17]. If accidents happen, they will delay the project, result in financial losses, or damage the company’s reputation [16].

Safety is widely acknowledged as essential, but there are large discrepancies in its application in different situations. The formulation and implementation of stringent health and safety (H&S) laws are poor in nations such as Nepal, and this has adversely affected the efficacy of the overall project [18]. A complete approach is required to achieve effective safety management in construction. Adherence to laws includes adherence to local safety standards, the provision of personal protective equipment, regular safety meetings, and elaborate training programs [19]. It is of paramount importance to develop a safety culture so that there is an atmosphere of supportive risk management [20]. There are several things that are responsible for accidents that occur in construction projects, such as human factors, equipment, the environment, and company policies. Over one quarter of accidents (25-38%) are attributed to worker behaviors that result from both improper equipment usage and the incorrect application of PPE [15, 21]. Errors due to poor training concerning safety rules and equipment operation rules can lead to accidents. Many employees will not have the requisite training to recognize hazards or respond appropriately in emergencies [11]. This training can eliminate physical and mental exhaustion, which lowers judgment and reaction times and thus elevates the risk of accidents. Long, continuous hours without appropriate breaks make employees tired [21]. Perilous situations can be generated by neglected sites, insufficient illumination, and unfavorable weather conditions, which increase the likelihood of accidents. For example, slips and falls may be caused by wet or muddy circumstances [11, 22].

The failure of machinery or equipment can lead to accidents, mostly due to a lack of maintenance or improper use. An organization with a weak safety culture can become complacent about safety procedures. A lack of safety prioritization by management affects how workers respond to safety [11]. Poor communication within the team about safety practices, such as hazards and emergency procedures, can result in a heap of misunderstandings that can lead to accidents. Methods of communicating in such environments need to be constructed to keep the construction site safe [11]. Inspections and maintenance are required to keep the equipment safe [21]. Safety is necessary for protecting workers from injuries and death. Worker safety is paramount in industries in which hazards are present, such as construction [23]. A safe working environment helps employees feel mentally healthy and well, decreases stress, and improves overall job satisfaction [17]. A project with a strong safety culture leads to improved worker morale. When employees are safe and valued, they are more productive and engaged in their work. Organizations with highly developed safety programs have lower turnover rates and higher employee satisfaction [10]. Organizations have to make their workplaces comply with Occupational Safety and Health Administration (OSHA) regulations and local laws [11, 24, 25].

2.1. Risk Management in Construction Safety

Risk management in construction projects is a vital aspect of the overall management process, focusing on three primary principles: time, cost, and quality [26]. The process involves the identification, analysis, and implementation of suitable treatments for risks existing in the complex and dynamic construction industry [27]. The construction risk management process typically includes planning for, identifying, evaluating, monitoring, and mitigating risks [28]. The aim is to reduce the chances of adverse events and increase the chances of favourable events [28]. However, the application of risk management techniques in the Somalian construction industry is greatly different from the use of these techniques in other countries, and therefore the local context should be considered [29].

Construction businesses can consistently attain exceptional performance while proactively dealing with risk through an integrated risk management strategy [30]. Risk analysis should be incorporated into project management in the construction sector, including probability and effect methodologies and more sophisticated methods such as artificial neural networks [31]. The execution of risk management can improve safety, protect the company's reputation, and reduce the costs of workplace incidents [28]. Construction safety risk management requires a multi-faceted approach. Real-time monitoring and early warning systems, accident and emergency response simulation, safety risk prediction and assessment, safety risk management decision support, and safety training and education should all be included in this approach [32].

The construction of bridges involves many different risk variables, and they are all interrelated. Shan et al. [4] found that there are numerous causes of accidents that occur during the construction of bridges: human factors, equipment factors, management factors, and environmental factors. Shan et al. [4] found that the combined risks from different risk variables may be extremely high, especially when it comes to human factors, as many other factors influence them. In addition, cutting-edge technologies such as three-dimensional laser scanning to monitor the safety of bridge building have also been utilized [3]. For effective risk management in bridge construction safety, the application of sophisticated assessment methodologies in the planning and design stages is required. For this approach to be effective, it must be comprehensive. The use of artificial intelligence algorithms such as random forest has been shown to achieve speedy and reliable risk assessment [33, 34].

2.2. Risk Identifications on Safety Construction

The WBS and RBS are efficient ways to identify safety hazards in construction projects. As a result, we can develop a systematic and complete methodology for identifying and assessing risk [35, 36]. In construction projects, a WBS is used to break the project into smaller units of work, and an RBS is used to classify and analyze potential risks. These structures are integrated into a WBS-RBS connection matrix [37] to identify WBS-specific risk variables. This has been successfully applied to a number of construction situations, including electric vehicle production, hydropower projects, and tunneling projects [35, 38]. The WBS-RBS methodology has many advantages in the identification of safety risks in construction. It supports a systematic and complete risk assessment, it facilitates risk variable prioritization, and it describes how to formulate targeted safety measures [35, 39]. This was the first method to identify critical risk elements in a lifting operation project when safety knowledge is not available: they include unlawful practices and deficient protective measures [39]. The accuracy of risk assessment in building projects can be improved using fuzzy logic and Bayesian networks with the WBS-RBS technique [35, 36].

The identification of construction safety concerns is carried out by applying the WBS and RBS, but they suffer from many difficulties. WBS-RBS is frequently employed for risk identification in building projects, but it may fail to cover some safety issues. The structures are built largely using the skills and experience of the participants, and the approach can result in subjective assessments and fail to properly identify the risk factors [40]. For the individual preferences, the subjectivity of this method may cause it to either underestimate the significance of some risks or overestimate others. Specifically, various studies endeavored to diminish this disadvantage by utilizing WBS-RBS with other methodologies. For example, in Fu et al. [40], the risk level of a building is evaluated on the basis of the matter element extension model and variable weight theory with risk variables. Chen et al. [35] also used WBS-RBS combined with fuzzy Bayesian networks to assess the fire risk due to electric vehicles. In these hybrid methodologies, researchers attempt to reduce subjectivity and increase the thoroughness of risk identification. Some research has developed complete index systems for risk assessment, such as the WBS-RBS matrix [10, 40, 41]. A matter element extension model is employed to quantify the identified risks. The variable weight theory is applied to this model, and it is used to assess the significance of various risk factors in a structured framework for construction risk evaluation [40].

Construction projects have many dangers and risks, which can seriously damage occupational health and safety. The identified and evaluated risks are needed to manage safety in the construction sector efficiently. Various methods have been used to identify and assess risks in construction safety. The hazard identification risk assessment and risk control (HIRARC) and failure mode effect analysis (FMEA) methodologies were used to identify and analyze potential hazards [42]. Alternative methodologies include the cost of safety (COS) model coupled with the AHP for the prioritization of safety risks [43] and attribute-based risk assessment models using data mining techniques for the analysis of injury reports and the correlation between hazardous activities and risks [44, 45]. Classical risk identification involves structured approaches, expert inputs, and a continuing process. The fuzzy AHP allows project managers to prioritize risks, which results in smarter decisions, reducing both the cost and time needed to decommission a nuclear power plant [41].

The application of intelligent construction in bridge engineering safety management is a developing trend. Modern information technology helps to promote the intelligent safety management of bridge engineering, but there are still challenges for future development [46]. Solutions have been provided as to how the complex safety risks involved in bridge construction have been managed. A new early-warning model that integrated a rough set (RS), the sparrow search algorithm (SSA), and the least squares support vector machine (LSSVM) has improved the accuracy of forecasting construction safety problems [47]. Another approach is to combine the cloud model with the uncertain AHP to address the vagueness and randomness of the evaluation of safety hazards in bridge building [48].

2.3. Risk Analysis on Safety Construction

Construction safety risk analysis is an important part of project management that includes many methods and technologies to identify, assess, and reduce potential risks. Conventional techniques such as job safety analysis (JSA) are tailored for construction settings [49], and these methodologies provide a sound framework for locating, assessing, and mitigating safety hazards across different construction projects. Chen et al. [50] suggest a dynamic risk analysis for behavior-based safety (BBS) management that combines expert experience with objective historical data to produce more accurate outcomes. Through graph topology analysis, this approach evaluates the risks and consequences of hazardous activities and improves the grey clustering model of construction site risk. Different methods have been used for certain construction situations. A bridge construction strategy based on the cloud model and the uncertain analytic hierarchy method to deal with fuzziness and unpredictability in risk assessment is proposed [48]. Safety in bridge construction has been assessed using backpropagation neural networks [51]. Additionally, for the transverse construction of bridges, three-dimensional laser scanning technology is used for point layout measurement, monitoring strategies, and data analysis [3]. The application of Building Information Modelling (BIM) technology has also been employed to improve the quality and effectiveness of construction safety management [52].

Machine learning algorithms may successfully be used to help identify safety concerns associated with tunnel construction through the identification of potential ground settlement and the determination of safety issues [53]. In risk analysis in utility tunnels, operational maintenance (O&M) is emphasized to lower the occurrence of hazards, e.g., fires or building failure. Global data integration is utilized to create advanced decision support systems to enhance emergency response capabilities [54, 55]. Digital twin technology is incorporated in safety analysis, not only to enhance real-time monitoring and decision-making abilities in complicated systems such as urban infrastructure [25, 56, 57] but also to improve safety assurance. Building sites can be monitored for environmental conditions and worker safety by means of the Internet of Things (IoT), allowing the real-time delivery of such data and improving decision-making in risk management [14, 15]. Enhancing project outcomes requires the incorporation of sophisticated technology and procedures in construction safety risk analysis. The monitoring of bridge building has been done using three-dimensional laser scanning technology [3].

Several criteria and approaches are involved in bridge construction safety risk analysis. Different methods have been used in diverse investigations to evaluate and mitigate these risks efficiently. There are many studies that highlight the use of sophisticated analytical methodologies for risk evaluation. Safety risk variables were assessed with the imprecise synthetic judgment approach and AHP, and a compilation of risk elements was created [58]. Questionnaire surveys and expert grading methodologies were used to examine risk factors with factor analysis, which showed six main risk factors influencing bridge-building safety [59]. To deal with the ambiguity and unpredictability in safety risk assessment, a cloud model and an uncertain AHP [48] were introduced. The bridge-building risk was assessed using the random forest algorithm to determine the importance of indicators and generate benefits, including precise and resilient risk assessment outcomes that are independent of expert evaluations [33, 34]. The cost and schedule implications of project risks were assessed through the use of a Monte Carlo simulation [60]. The Monte Carlo simulation was used to evaluate and mitigate schedule risks in both feasibility studies and construction stages. This approach helped project managers cut down on potential delays and budget overruns [60].

2.4. Application AHP and Rating on Safety Construction

Numerous research studies have proved that the AHP can be effectively used to evaluate construction safety issues. The AHP was used to identify and rank risk factors in Metro Manila condominium projects related to the health and safety risk (19.52%), quality risk (15.97%), and management/supervision risk (15.77%) [35]. To research bridge construction safety based on critical aspects of occupational safety and hygiene management, such as electrocution, which was one of the risk factors that might be underreported compared to fall injuries, the AHP was used. Construction safety risk analysis has been performed using the AHP, and some discrepancies have been found between the AHP and conventional evaluations. Previous safety evaluations [61] suggested that electrocution was a greater problem than fall injuries, but the results of the bridge construction investigation indicated otherwise. This suggests that the AHP can provide novel insights and points of view as to risk components that are likely to be overlooked if standard techniques are employed. Construction safety risk management has made extensive use of the AHP, but it has been found to be deficient in interdependencies. The assumption of independence is made in the AHP, which is not always true in building projects, where most of the risks are interdependent. This constraint will result in the oversimplification of the risk assessment procedure [62, 63].

The safety assessment of bridge structures using the AHP has been applied extensively to long-span bridges, e.g., suspension bridges. As an example, an AHP model was combined with fuzzy logic for decision-making to assess the safety of single-tower steel box girder suspension bridges over the sea. This method, wherein the weights of various factors such as the cable tension, the load on the main tower, the wind speed, and ambient conditions were determined together, gave a complete evaluation of the safety of the bridge [64]. In another study, a combination of the AHP, the best-worst method (BWM), and data envelopment analysis (DEA) was used to examine the risks faced by tunnel-boring machine operations during metro construction [65]. In building safety assessment, especially for public-use buildings susceptible to disasters such as fires and earthquakes, the AHP is also applied. For instance, the AHP was used to derive an integrative building safety evaluation framework to rank safety categories that included fire safety, electrical systems, gas systems, and crime prevention categories [66]. An integrated approach using the spherical fuzzy AHP to study shipyard floating-dock operations assessed occupational hazards through the evaluation of different risk factors (consequence, frequency, probability, and number of people exposed) [67].

The AHP has been extensively applied in construction safety management to systematically assess and rank safety concerns. Its application in several areas of construction safety has been demonstrated by several studies. The AHP has been employed to establish safety risk evaluation systems for manufactured buildings, identifying 17 critical risk elements across five dimensions: the material, management, human, machine, and environment dimensions [68]. It is a safety protocol prioritizing strategy because it allows one to concentrate on safety where it matters: site safety personnel, operator proficiency, and equipment maintenance. The AHP is applied to the safety assessment of emergency training scenarios involving human, machine, environmental, and managerial aspects related to building collapse [69].

The AHP is widely used in construction management, especially in risk management and sustainable construction, but unfortunately it has some limitations. The AHP has been shown to be subject to limited sample sizes and the subjective characteristics of pairwise comparisons [70]. However, it offers adaptability and the potential to be combined with alternative methodologies [69] to increase its applicability in complex decision-making scenarios. This paper studies the use of the AHP in risk evaluation in building projects and the incorporation of other methodologies to improve the efficacy. A model proposed by Du & Han [71] that combines the AHP with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is used to assess safety management in building projects.

Safety evaluation in bridge construction projects is surveyed, and the extensive use of the AHP in systematizing and ranking a wide range of risk factors is illustrated. Several studies have combined the AHP methodology with other approaches to refine and reinforce the accuracy and reliability of safety assessments. The AHP analysis of occupational safety in bridge construction showed that electrocution is more dangerous than fall injuries [61], and several studies have disclosed unforeseen results. This is a motivation to thoroughly evaluate risk variables to get to the subtle risks. The use of the AHP to provide safety assessments for bridge building has been demonstrated to be a versatile and easy method. It includes the study of the effect of road construction on existing bridges [72] and occupational safety [61].

This research integrates the WBS and RBS to comprehensively identify hazards: the WBS is used to construct a hierarchical breakdown of the safety analysis process, and the RBS is used to establish a comprehensive categorization of safety risks. The WBS and RBS are combined to form a systematic risk management methodology that helps project managers to synchronize the management of strategy with the management of projects. The integration of these two methodologies enhances the ability to detect, assess, and rank risks and thus provides more efficient risk mitigation and improved project outcomes [35]. The integration provides a systematic way to identify safety hazards associated with specified tasks in the WBS. By linking these tasks with resources in the RBS, project managers can better understand the potential relationship between risks and available resources [73]. By integrating the WBS and RBS, potential hazards associated with task execution and resource availability are identified. That is, this proactive approach promotes improved risk assessment and reduction across the entire project life cycle [74]. Working with an RBS allows the classification of hazards according to historical data, which are linked to certain tasks in the WBS.

The AHP method is used in this research because the AHP in safety applications uses expert knowledge and criterion weights [75]. Another reason for using it is the possibility of linking it with other tools, which makes it a useful method to improve safety-related decision-making procedures in different fields of activity [70, 76]. Then, the AHP assists in determining the weights of the many safety risk factors for construction site safety with more rationality compared to other approaches [77]. Furthermore, to assess the relative importance of each factor, AHP matrices were created for each of the categories of factors, where pairwise comparisons were made [78]. The model proposed in this study integrates the WBS-RBS, AHP, and rating methods, as presented in Figure 1. The advantages of each method are used to refine the identification and assessment of safety risks in construction projects.

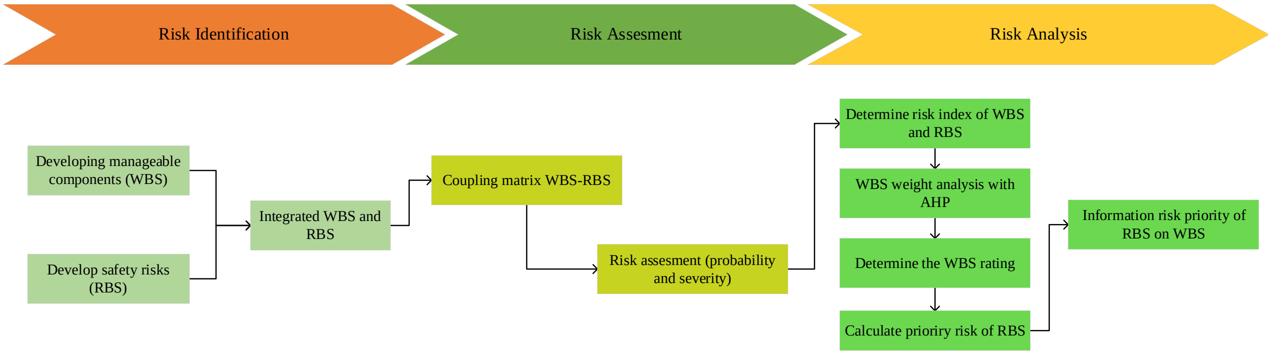

Figure 1. Proposed model

3. Research Methodology

The first stage determines the types of risks and tasks in bridge construction. Data about types of accidents and work stages are collected from references, and experts who know how to build bridges are interviewed. Risk types are identified as an RBS, and work stages are identified as a WBS. The integration of the WBS activity stages and RBS risk types follows, and an assessment list for probability and severity is compiled. After the completion of the respondents' probability and severity assessment forms, the following assessment stage is completed. The data were collected through the stratified random sampling method, where respondents were selected in accordance with the criteria of having experience in bridge work and working for contractors, consultants, or the government.

The data are then collected and compiled to get the risk index based on the WBS and RBS. The result of this calculation is a global score of the RBS risk index; then, we use the AHP method to analyze this score to find the weights of the WBS work stages. AHP analysis is used to calculate WBS weights in the WBS-RBS matrix coupling, with the resulting matrix corresponding to the number of WBS stages at the lowest level related to the RBS. This matrix is a pairwise comparison to determine the relative importance of criteria analyzed using the AHP calculation procedure to obtain priority weights. This priority weight is analyzed using the rating method to obtain a proportional scale for calculating the RBS risk index. The results of the WBS rating analysis will be multiplied by the RBS risk index to give the RBS risk index at those WBS stages. These data can reveal the highest RBS accident risk in the associated WBS work. A flow diagram of the model used to analyze the safety risks of bridge construction is shown in Figure 2.

Risk identification using the WBS and RBS forms a matrix of the WBS and RBS at the lowest level of the WBS and RBS. We analyze the formed matrix by arranging it into a paired matrix, which matches the number of identified risks at the lowest level of the RBS. The WBS is a method of organizing and defining all the project's working ranges by arranging project aspects. The WBS sub-grade denotes a more intricate project. As the lowest grade of the WBS, the work package (WP) provides the rationale for defining the activities and assigning tasks to the individual and the organization. A hierarchical arrangement of the possible risk sources is known as an RBS. A method for grouping project risks facing the project, the RBS organizes and specifies all the project's risks with reference to the WBS definition. The RBS sub-grade is a more specific source of the project risk. The fundamental idea behind WBS-RBS risk identification is that, based on the establishment of a reasonable WBS and RBS, the risk of each WP within the effective working range specified in the WBS will be determined in accordance with the particular risk factors specified in the RBS.

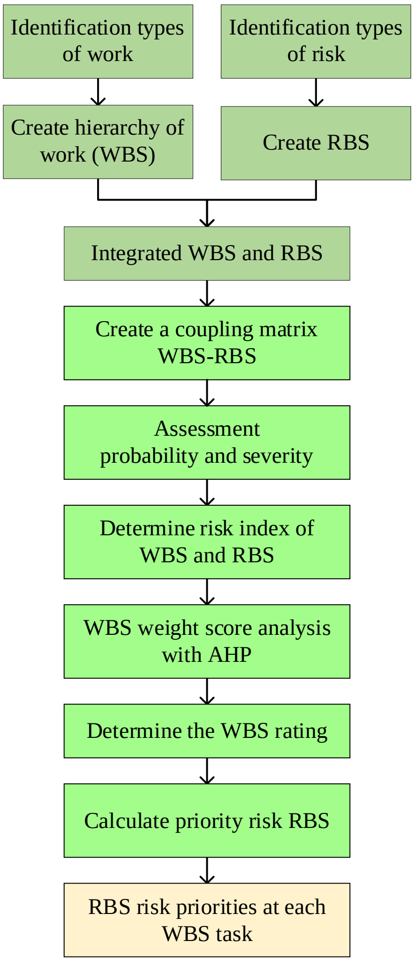

Figure 2. Safety Risk Assessment Model Flowchart

After obtaining the coupling matrix model from the WBS and RBS, respondents conduct a risk assessment, evaluating the probability and severity that will inform the analysis of the construction safety risk index for bridge construction (Figure 3). The results of the risk index analysis were then grouped by risk level using the risk matrix presented in Table 1. For probability, the scale is 1 for rare, 2 for unlikely, 3 for moderate, 4 for likely, and 5 for almost certain. For severity, the scale is 1 for negligible, 2 for minor, 3 for moderate, 4 for major, and 5 for catastrophic. The four risk categories are as follows: extreme has a range of 17–25, high has a range of 9–16, moderate has a range of 5–8, and low has a range of 1–4.

Table 1. Risk Level Matrix

		Severity				
		Negligible	**Minor**	**Moderate**	**Major**	**Catastrophic**
Probability	Rare	L	L	L	L	M
	Unlikely	L	L	M	M	H
	Moderate	L	M	M	H	H
	Likely	L	M	H	H	E
	Almost certain	M	H	H	E	E

Note: L low risk, M: moderate risk, H: high risk, E: extremely high risk.

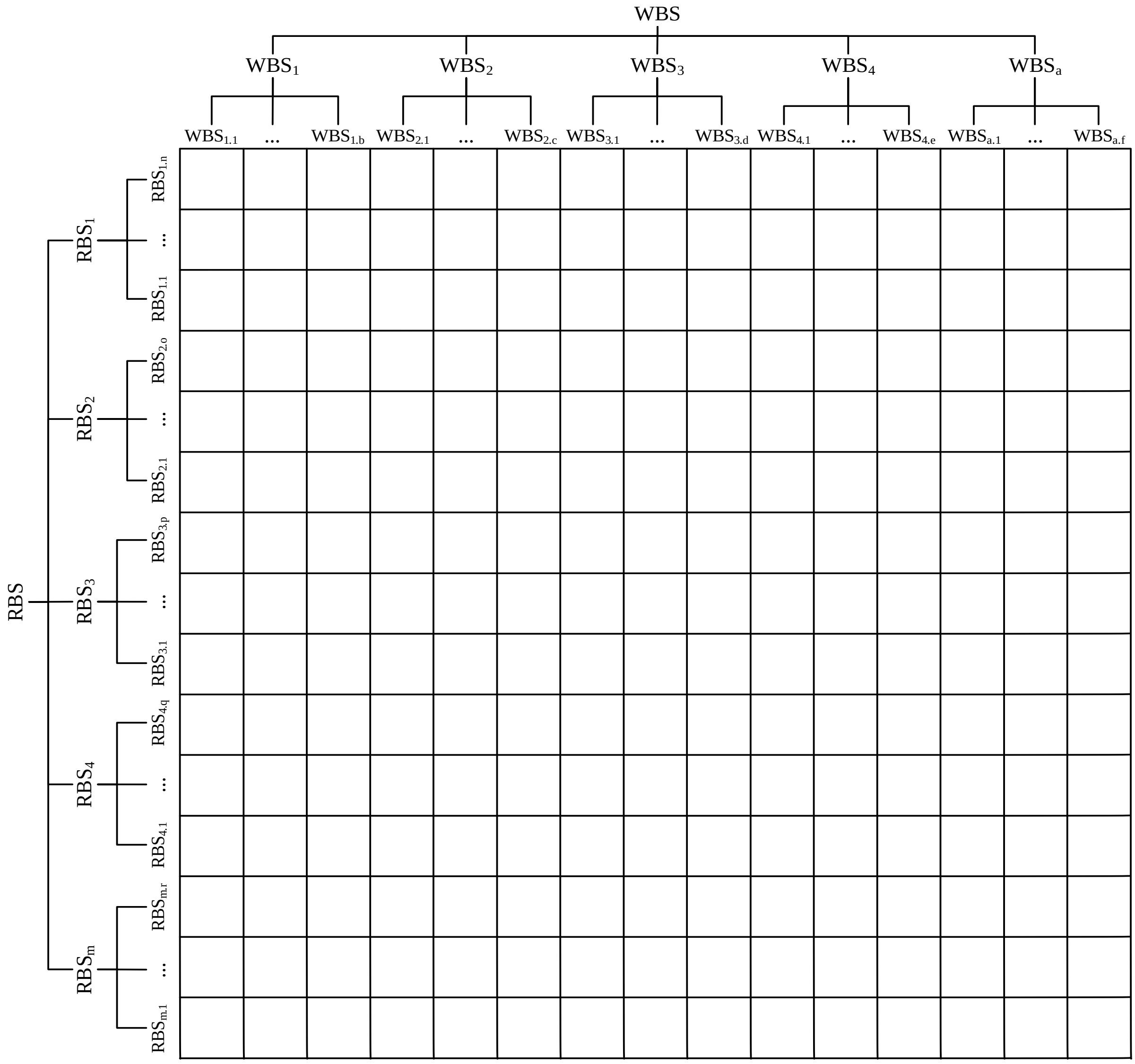

Figure 3. Model WBS-RBS coupling matrix

The AHP analysis comprises several steps: constructing the pairwise comparison matrix, determining the priority vector for a criterion such as experience, calculating the consistency ratio, computing λmax, deriving the consistency index (CI), selecting a random value for the CI from a table, and evaluating the consistency of the pairwise comparison matrix to ascertain whether the decision-maker's comparisons were consistent (below 10%). The geometric mean approach involves the assessment of the priority vector obtained from the root (number of rows) of the product of the rows of the pairwise matrix (a_i) as follows:

$$GM = \sqrt[n]{\prod_{i=1}^{n} a_i} \tag{1}$$

The consistency vector represents a comparison between the weight square matrix and the priority vector. The weight square matrix (WSM_i) is derived by multiplying the pairwise comparison matrix (M_{ij}) with the priority vector matrix (PV_i), as described by the following Equation:

$$WSM_i = \sum_{j=1}^{m} \sum_{i=1}^{n} M_{ij} PV_i \tag{2}$$

The consistency index is obtained from the maximum eigenvalue of the paired matrix (λmax) and the dimension of the paired matrix (n), and the consistency ratio (CR) is the comparison of the consistency index (CI) and the random index (RI). These values are determined using the following Equations:

$$CI = \frac{\lambda max - n}{n-1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

The AHP is utilised to evaluate the significance of each activity and hazard, improving the assessment of workplace accident risk within the relevant WBS. Upon normalising the WBS weights, a rating is produced that serves as a multiplier to determine the RBS distribution; this rating is the ratio of the priority weight (Wi) on each RBS risk to the maximum value of the priority weight (Wj), and it is computed using the Equation 5:

$$\text{Idealised} = \sum_i^n \frac{w_i}{\max \sum_j^m w_j} \tag{5}$$

4. Results and Discussion

4.1. Respondent Description

There were 48 participants overall, 46 men and 2 women. Construction projects in Indonesia are male-dominated, and hence there is a preponderance of male respondents in the acquired data. The ages of the respondents are mostly in the range of 37 to 42 years, and the work experience ranges from a minimum of 5 years to a maximum of 34 years. The education levels range from doctoral to associate degrees, with 31 respondents having a bachelor's degree and a PhD degree being the most uncommon. There are 31 contractors, 13 consultants, and 4 government entities employing the respondents. The role of employment includes the following: 7 project managers, 7 supervisors, 21 project engineers, 3 quality control staff, and 10 Quality, Health, Safety, and Environment (QHSE) professionals. The profiles of the respondents are presented in Table 2.

Table 2. Description Of Respondents

No.	Description	Classification					
1	Gender	Male			Female		
		46			2		
2	Age (year)	25-30	31-36	37-42	43-48	49-54	55-60
		8	13	15	5	4	3
3	Work experience (year)	5-9	10-14	15-19	20-24	25-29	30-34
		17	15	6	8	1	1
4	Education level	S3	S2	S1	D4	D3	
		1	7	31	3	6	
5	Workplace	Contractor		Consultant		Government	
		31		13		4	
6	Job positions	J1	J2	J3	J4	J5	
		7	60	21	3	10	

Notation: D3: associate degree, D4: Bachelor of Applied Science, S1: bachelor, S2: master, S3: doctoral, J1: Project Manager, J2: Supervisor, J3: Project Engineering, J4: Quality Control, J5: HSE

4.2. Risk Identification

Risk identification begins by breaking down bridge construction into four levels according to the stages of bridge construction. The first level is the main work, the second level is the main sub-work, and level 3 contains the details of the sub-work. The main task is divided into two tasks, namely substructure activities (W1) and superstructure activities (W2). The substructure task is broken down at level 3 into earthwork (W1.1), foundation (W1.2), pile cap (W1.3), and pier (W1.4). The earthwork task is divided at level 4 into soil excavation (W1.1.1), landfill (W1.1.2), hauling (W1.1.3), and dewatering (W1.1.4). The foundation task is broken down into piling preparation (W1.2.1), pile transportation (W1.2.2), pile driving (W1.2.3), pile connection (W1.2.4), pile cutting (W1.2.5), pile scrap disposal (W1.2.6), bridge abutment (W1.2.7), and abutment (W1.2.8). The last substructure task is pile cap, which is broken down into floor work (W1.3.1), pile cap reinforcement (W1.3.2), pile cap formwork (W1.3.3), and pile cap concrete pouring (W1.3.4).

The superstructure task at level 3 is broken down into girder fabrication (W2.1), girder storage (W2.2), girder and diaphragm installation (W2.3), bridge main deck (W2.4), and parapets (W2.5). The girder fabrication task is divided into girder fabrication reinforcement (W2.1.1), girder fabrication formwork (W2.1.2), and girder fabrication concrete pouring (W2.1.3). The bridge main deck task is broken down into bridge main deck reinforcement (W2.4.1), bridge main deck formwork (W2.4.2), and bridge main deck concrete pouring (W2.4.3). The last part of the superstructure is divided into parapet reinforcement (W2.5.1), parapet formwork (W2.5.2), and parapet concrete pouring (W2.5.3).

The RBS identifies the potential risks of bridge construction and identifies various risks that cause accidents from the substructure stage to the superstructure stage. Data were collected from two sources: journals and staff working on the bridge project. At level 2, the RBS identified 24 potential risks, which can be classified into human aspects (R1), such as workers being exposed to welding (R1.1), scalded skin being exposed to concrete (R1.2), workers being stabbed by sharp objects (R1.3), workers being hit by heavy equipment or trucks (R1.4), workers' bodies being scratched (R1.5), workers falling (R1.6), workers being pinched in equipment (R2), equipment falling into a river (R2.1), and heavy equipment or trucks overturning (R2.2). The material aspects (R3) include reinforcement collapse (R3.1), formwork collapse (R3.2), a girder being broken (R3.3), a girder rolling over (R3.4), a girder falling during erection (R3.5), pile overturning (R3.6), and earth wall collapse (R3.7).

This research involves applying a WBS as the basic tool to organize and manage the project, which decomposes the project into smaller, more manageable units. The WBS is a hierarchical decomposition of the work that is to be done. The phases of the project itself are clearly defined. Especially for bridge construction, there are usually many activities, resources, and risks that it is important to coordinate very carefully. The main goal of the WBS in bridge building is helping to reveal all of the tasks and their composition in such a way that project planning, execution, monitoring, and control can be organized. It breaks the project into smaller work packages or deliverables that teams or contractors can be assigned for implementation. The results of the WBS identification show four levels of the WBS, namely Level 1 - Overall project (bridge construction); Level 2 - Major phases (substructure and superstructure); Level 3 - Specific tasks within each phase (for example, foundation, pile cap, girder); and Level 4 - Detailed activities and resources for each task (concrete pouring, concrete formwork, concrete reinforcement).

This research uses an RBS to develop a hierarchical framework to identify, categorize, and manage risks systematically in bridge construction projects. The RBS provides the project manager and the stakeholders with an idea of the risks that could affect different aspects of the project, such as design and materials, environmental conditions, and human resources. The RBS organizes risks into structured categories and provides a comprehensive overview of uncertainties in bridge construction that facilitates the development of effective risk mitigation strategies. Bridge construction risks are normally classified into three categories, namely human aspects, equipment aspects, and material aspects (see Figure 4).

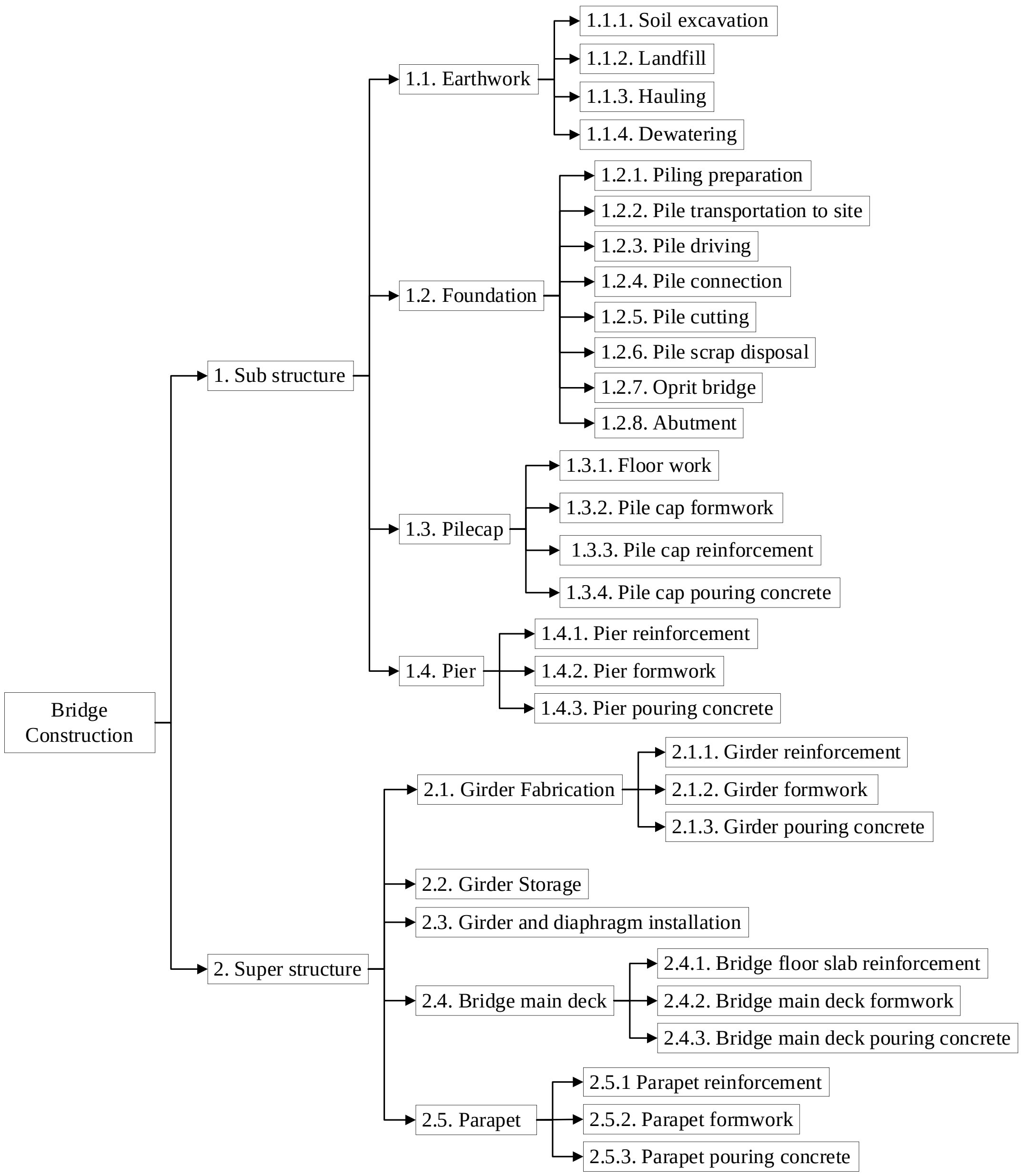

Figure 4. Break down WBS in Bridge Construction

The established WBS and RBS indicate that the lower-level units of both frameworks are interrelated to formulate the coupling matrix for identifying construction hazards in bridge projects. In this matrix, '0' denotes the absence of risk from the interconnection, and '1' shows the presence of created risk. In formulating the coupling matrix, we initially verify that each item (W) and each risk category (R) in the RBS are distinctly recognized. Subsequently, by pairing them individually, we establish a junction for each pair, W and R, that signifies if W poses a risk during building. The risk associated with the human element is derived from the convergence of soil excavation (W1.1.1) with worker exposure to welding (R1.1), potential impacts from heavy equipment or trucks (R1.4), worker slips (R1.9), worker entrapment (R1.10), the overturning of heavy equipment or trucks (R2.2), and the collapse of reinforcements (R3.1). The outcomes of the WBS and RBS integration matrix for bridge construction are displayed in Tables 3 and 4.

Table 3. Coupling Matrix of WBS and RBS on Bridge Sub Structure

		W1																		
		W1.1				W1.2								W1.3				W1.4		
		W1.1.1	W1.1.2	W1.1.3	W1.1.4	W1.2.1	W1.2.2	W1.2.3	W1.2.4	W1.2.5	W1.2.6	W1.2.7	W1.2.8	W1.3.1	W1.3.2	W1.3.3	W1.3.4	W1.4.1	W1.4.2	W1.4.3
R1	R1.1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	R1.2	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1
	R1.3	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	R1.4	1	1	1	1	0	1	1	0	1	0	0	1	0	0	0	1	1	1	1
	R1.5	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	1	0	1	1
	R1.6	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	1	1
	R1.7	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	R1.8	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	R1.9	1	1	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
	R1.10	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
	R1.11	0	0	0	0	0	1	1	0	0	1	0	0	1	1	1	0	1	1	1
	R1.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R1.13	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	R1.14	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1
	R1.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0
R2	R2.1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
	R2.2	1	1	1	0	0	1	1	1	0	1	1	1	0	0	1	1	1	1	1
R3	R3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	R3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	R3.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.6	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
	R3.7	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0

The WBS and the RBS are two important tools for organizing and managing the project; in this research, the WBS and RBS are integrated into bridge construction. For comprehensive project planning and risk management, the mapping of risks to work packages is essential, which means that for every work package (WBS) defined, the risks from the RBS can be mapped to. By correlating certain project tasks with their related risks, the project manager can focus on mitigation efforts for high-risk activities. The WBS makes sure that everyone knows what needs to be done, and the RBS makes sure that everyone is aware of what risks might occur and how they will be managed. The bridge construction project integration of the WBS and RBS offers a structured approach to manage both work activities and the associated risks. Additionally, this integration guarantees that risks are constantly addressed at each of the phases of the project. Through mapping out specific risks for individual work packages, project teams can develop specific mitigation strategies, which, when applied, will contribute to the overall project success while reducing delays and cost overruns.

Table 4. Coupling Matrix of WBS and RBS on Bridge Super Structure

		W2										
		W2.1			**W2.2**	**W2.3**	**W2.4**			**W2.5**		
		W2.1.1	**W2.1.2**	**W2.1.3**			**W2.4.1**	**W2.4.2**	**W2.4.3**	**W2.5.1**	**W2.5.2**	**W2.5.3**
R1	R1.1	0	0	0	0	0	0	0	0	0	0	0
	R1.2	0	0	1	0	0	0	0	1	0	0	1
	R1.3	0	1	1	1	0	0	0	0	1	1	1
	R1.4	1	1	1	1	1	1	1	1	1	1	1
	R1.5	1	1	1	0	0	1	1	1	1	1	1
	R1.6	0	0	0	0	1	1	1	1	1	1	1
	R1.7	0	0	0	0	0	0	0	0	0	0	0
	R1.8	0	0	0	0	0	0	0	0	0	0	0
	R1.9	0	0	0	0	0	0	0	0	0	0	0
	R1.10	0	0	0	0	0	0	0	0	0	0	0
	R1.11	0	0	0	0	1	1	1	0	1	1	1
	R1.12	0	0	0	1	1	0	0	0	0	0	0
	R1.13	0	0	0	0	0	0	0	0	0	0	0
	R1.14	0	0	1	0	0	0	0	1	0	0	1
	R1.15	1	0	0	0	0	0	0	0	0	0	0
R2	R2.1	0	0	0	0	0	0	0	0	0	0	0
	R2.2	1	1	1	1	1	1	1	1	1	1	1
R3	R3.1	0	0	0	0	0	0	0	0	0	0	0
	R3.2	0	1	0	0	0	0	1	0	0	1	0
	R3.3	0	0	0	1	1	0	0	0	0	0	0
	R3.4	0	0	0	1	1	0	0	0	0	0	0
	R3.5	0	0	0	0	1	0	0	0	0	0	0
	R3.6	0	0	0	0	0	0	0	0	0	0	0
	R3.7	0	0	0	0	0	0	0	0	0	0	0

4.3. Risk Assessment Probability and Severity

Risk assessment is conducted by respondents who have been selected based on their job position, education, and length of service. Respondents evaluate the probability and severity of risks from the WBS and potential risks (RBS) that have occurred over the past 6 months. The type of bridge object assessed according to the WBS created is a bridge with concrete girders and pile foundations. The risks at the construction stage of the bridge are divided between the substructure and the superstructure, where the superstructure carries a greater risk compared to the substructure. The highest risk in the substructure is found in the pier work (W1.4), with a risk index of 9.3281, followed by the foundation (W1.2) at 8.6771, earthwork (W1.1) at 7.6497, and pile cap (W1.3) at 6.9427. The highest risk stage in earthwork occurs in soil excavation (W1.1.1) at 5.0347, the highest risk in the foundation occurs in abutment work (W1.2.8) at 6.2708, the highest risk in the pile cap occurs in reinforcement work (W2.3.2), and the highest risk in pier work also occurs in reinforcement work (W2.3.2). The complete results of the risk index analysis are presented in Table 5.

Table 5. Risk index of WBS on bridge sub structure

WBS	Description WBS	Probability	Severity	RI
1.	Sub Structure	2.3333	3.0833	7.1944
2.	Super structure	3.7917	4.2083	15.9566
1.	**Sub Structure**			
1.1.	Earthwork	2.9375	2.6042	7.6497
1.2.	Foundation	2.8333	3.0625	8.6771
1.3.	Pile cap	2.6875	2.5833	6.9427
1.4.	Pier	2.2500	4.1458	9.3281
1.1.	**Earthwork**			
1.1.1.	Soil excavation	2.4167	2.0833	5.0347
1.1.2.	Landfill	2.1875	1.6458	3.6003
1.1.3.	Hauling	2.1458	1.9792	4.2470
1.1.4.	Dewatering	2.3125	1.8750	4.3359
1.2.	**Foundation**			
1.2.1.	Piling preparation	1.6667	1.6458	2.7431
1.2.2.	Pile transportation to site	1.6875	1.7292	2.9180
1.2.3.	Pile driving	2.3125	2.2292	5.1549
1.2.4.	Pile connection	1.6458	1.2500	2.0573
1.2.5.	Pile cutting	1.3750	1.3125	1.8047
1.2.6.	Pile scrap disposal	1.2708	1.1667	1.4826
1.2.7.	Oprit bridge	2.1875	2.2708	4.9674
1.2.8.	Abutment	2.6875	2.3333	6.2708
1.3.	**Pile cap**			
1.3.1.	Floor work	1.2083	1.2083	1.4601
2.3.2.	Pile cap reinforcement	2.2173	2.1398	4.7446
2.3.3.	Pile cap formwork	2.0778	2.1553	4.4782
2.3.4.	Pile cap concrete pouring	2.0623	1.7211	3.5495
1.4.	**Pier**			
2.4.1.	Pier reinforcement	2.9792	2.8750	8.5651
2.4.2.	Pier formwork	2.7917	2.8958	8.0842
2.4.3.	Pier concrete pouring	2.7708	2.3125	6.4076

The superstructure consists of girder fabrication (W2.1), girder storage (W2.2), girder and diaphragm installation (W2.3), bridge main deck (W2.4), and parapets (W2.5); girder and diaphragm installation (W2.3) is the highest risk (12.0990) and is in the high-risk category. The medium-risk tasks are girder storage (W2.2), with a risk index of 5.2448; bridge main deck (W2.4), with a risk index of 6.2344; and parapets (W2.5), with a risk index of 5.9974. The results of the risk index analysis for the superstructure are presented in Table 6.

A bridge construction risk assessment (RBS) is conducted for the human aspect (R1), equipment aspect (R2), and material aspect (R3). Risks associated with labor activities during bridge construction are related to the human aspect. For this aspect, there is one high-risk category, workers falling (R1.6), with a risk index of 11.8403. There are two medium-risk categories: workers slipping (R1.9) and workers becoming stuck (risk index of 5.0469). The equipment aspect is related to the work-related risks of the tools used. Regarding the risk, the highest risk is shown by heavy equipment or a truck overturning (R2.2), with a risk index of 5.0104, in the medium category. The material aspect of the bridge involves the materials used in the construction of the bridge. None of these risks fall into the low category; they are all in the medium and high categories. Of all the reviewed aspects, girder falls during erection (R3.6) have a risk index of 15.8021 (the highest of all reviewed aspects). Other risks, such as reinforcement collapse (R3.1), formwork collapse (R3.2), earth wall collapse (R3.3), girders breaking (R3.4), girders rolling over (R3.5), girders falling during erection, and the pile overturning (R3.7), are in the moderate-risk category. The risk index analysis results for the superstructure are presented in Figure 5.

Table 6. Risk index of WBS on bridge super structure

WBS	Description WBS	Probability	Severity	RI
2.	**Super structure**			
2.1.	Girder fabrication	2.2500	2.1875	4.9219
2.2.	Girder storage	2.2083	2.3750	5.2448
2.3.	Girder and diaphragm installation	2.8750	4.2083	12.0990
2.4.	Bridge main deck	2.3750	2.6250	6.2344
2.5.	Parapets	2.9375	2.0417	5.9974
2.1.	**Girder Fabrication**			
2.1.1.	Girder Fabrication reinforcement	1.5719	1.5170	2.3845
2.1.2.	Girder Fabrication formwork	1.4730	1.5280	2.2507
2.1.3.	Girder Fabrication concrete pouring	1.4620	1.2202	1.7839
2.4.	**Bridge main deck**			
2.4.1.	Bridge main deck reinforcement	1.9911	1.9215	3.8259
2.4.2.	Bridge main deck formwork	1.8658	1.9354	3.6111
2.4.3.	Bridge main deck concrete pouring	1.8519	1.5455	2.8621
2.5.	**Parapets**			
2.5.1.	Parapets reinforcement	1.9154	1.8484	3.5405
2.5.2.	Parapets formwork	1.7949	1.8618	3.3417
2.5.3.	Parapets concrete pouring	1.7815	1.4868	2.6487

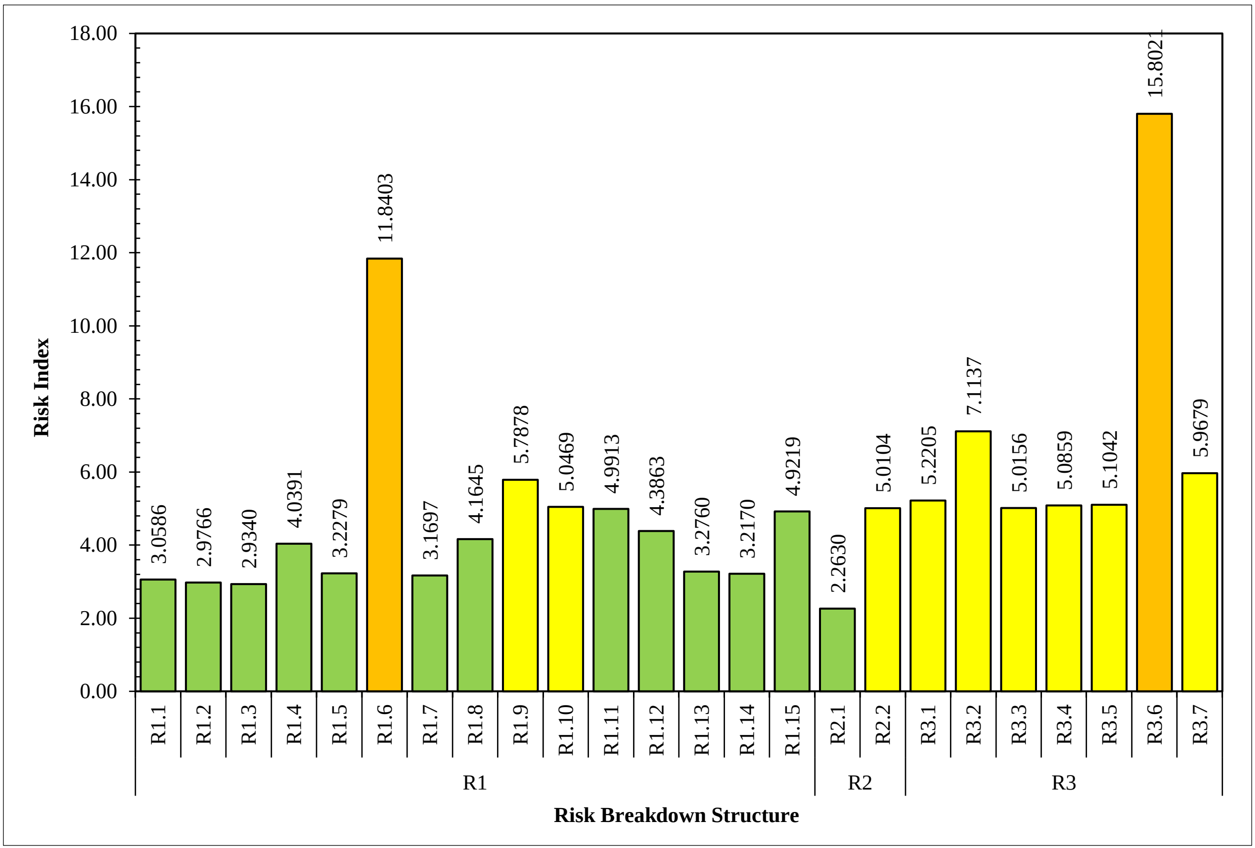

Figure 5. Risk index of RBS on bridge construction

The success of a project requires both a detailed WBS and a comprehensive RBS. The WBS organizes tasks into manageable components with clear resource requirements, and the RBS identifies the risk at each stage of construction and mitigates it. These two structures can be integrated to better plan for and manage risk and to communicate throughout the project life cycle. This process of bridge construction risk assessment involves the identification of risks, the determination of the probability and severity of risks, and the prioritization of risks based on the risk matrix. The method estimates the probability that a given risk event will occur during project construction, and the severity was used to estimate the potential consequences (or severity) of a risk event occurring, which could affect the project costs, schedule, safety, or structural integrity. The development of these effective mitigation strategies, which improve safety and manage delays and costs throughout the project life cycle, requires a systematic approach. During construction, new risks may arise, requiring new risk assessments to be performed periodically.

4.4. WBS Risk Weight Analysis with AHP

AHP analysis is done on the pairwise matrix that is made by comparing the risk indices of the WBS and the RBS. We use the pairwise matrix of the RBS at level R1.6 as an example. In RBS R1.6, there are 12 related WBS tasks: driving piles (W1.2.3), building an abutment (W1.2.8), reinforcing piers (W1.4.1), constructing piers (W1.4.2), pouring concrete into piers (W1.4.3), installing girders and diaphragms (W2.3), reinforcing bridge main decks (W2.4.1), constructing bridge main decks (W2.4.2), pouring concrete into the bridge main deck (R 2.4.3), reinforcing parapets (W2.5.1), building parapets (W2.5.2), and pouring concrete into parapets (W2.5.3). We construct the paired matrix by comparing the risk indices in the WBS, as displayed in Table 7.

Table 7. Pairwise matrix on RBS worker fall (R1.6)

R1.6	W1.2.3	W1.2.8	W1.4.1	W1.4.2	W1.4.3	W2.3	W2.4.1	W2.4.2	W2.4.3	W2.5.1	W2.5.2	W2.5.3
W1.2.3	1	0.82	0.60	0.64	0.80	0.43	2.16	2.29	1.80	1.46	1.54	0.80
W1.2.8	1.22	1	0.73	0.78	0.98	0.52	2.63	2.79	2.19	1.77	1.88	0.98
W1.4.1	1.66	1.37	1	1.06	1.34	0.71	3.59	3.81	2.99	2.42	2.56	1.34
W1.4.2	1.57	1.29	0.94	1	1.26	0.67	3.39	3.59	2.82	2.28	2.42	1.26
W1.4.3	1.24	1.02	0.75	0.79	1	0.53	2.69	2.85	2.24	1.81	1.92	1.00
W2.3	2.35	1.93	1.41	1.50	1.89	1	5.07	5.38	4.23	3.42	3.62	1.89
W2.4.1	0.46	0.38	0.28	0.29	0.37	0.20	1	1.06	0.83	0.67	0.71	0.37
W2.4.2	0.44	0.36	0.26	0.28	0.35	0.19	0.94	1	0.79	0.64	0.67	0.35
W2.4.3	0.56	0.46	0.33	0.35	0.45	0.24	1.20	1.27	1	0.81	0.86	0.45
W2.5.1	0.69	0.56	0.41	0.44	0.55	0.29	1.48	1.57	1.24	1	1.06	0.55
W2.5.2	0.65	0.53	0.39	0.41	0.52	0.28	1.40	1.48	1.17	0.94	1	0.52
W2.5.3	1.24	1.02	0.75	0.79	1.00	0.53	2.69	2.85	2.24	1.81	1.92	1

The AHP analysis is presented in Table 8; the pairwise matrix is analyzed using the geometric mean method to obtain the weights of each WBS phase and to calculate the consistency ratio. The calculation of the geometric mean uses formula (2); then, the priority vector from the WBS is calculated by normalising the geometric mean results. The consistency ratio check is performed by calculating the consistency vector using the weighted squared matrix obtained with formula (3) divided by the priority vector. The value of lmax is the average of the consistency vector of 12 tasks, so the resulting consistency index is 0, indicating that the data are consistent. AHP analysis is applied to all RBS risk at the lowest level to obtain the weight of each stage of the WBS phase, followed by a rating analysis used to derive the RBS value based on the WBS weight.

Table 8. AHP weight analysis on RBS worker fall (R1.6)

	GM	PV	WSM	CV
W1.2.3	1.05	0.08	0.92	12.00
W1.2.8	1.27	0.09	1.12	12.00
W1.4.1	1.74	0.13	1.53	12.00
W1.4.2	1.64	0.12	1.44	12.00
W1.4.3	1.30	0.10	1.14	12.00
W2.3	2.46	0.18	2.16	12.00
W2.4.1	0.48	0.04	0.42	12.00
W2.4.2	0.46	0.03	0.40	12.00
W2.4.3	0.58	0.04	0.51	12.00
W2.5.1	0.72	0.05	0.63	12.00
W2.5.2	0.68	0.05	0.60	12.00
W2.5.3	1.30	0.10	1.14	12.00
	13.69	1.00		12.00

The WBS and RBS are closely integrated in bridge construction for risk identification, categorization, and management during different phases of the project. The AHP can be used as a decision-making tool to rate these risks as to their probability and severity and give each a weight based on the priority of the risk. The AHP is a useful decision-making tool for assessing and prioritizing safety risks in bridge construction projects. The AHP assigns weights to different safety factors and risks to assist project managers in making informed decisions to increase safety in the construction process. Safety-weighted analysis in bridge construction through AHP implementation enables project managers to systematically evaluate and prioritize safety risks related to different work packages. This approach integrates expert judgment with quantitative risk assessments to improve decision-making processes and consequently improve safety in construction practices and project outcomes.

4.5. RBS Risk Index Rating Analysis at WBS Task

Rating analysis using formula (6) is used to determine the priority of the RBS for the related WBS; in this example, RBS R1.6, worker falling, is used. The risk index rating is the product of the global R1.6 and the rating value; the result shows that the highest risk of R1.6 occurs in the activity W2.3, girder and diaphragm installation. The complete risk index rating analysis for RBS worker falling (R1.6) is presented in Figure 6. This stage is carried out for all RBS risks, and the overall rating analysis results are displayed in the WBS-RBS integration matrix presented in Tables 9 and 10.

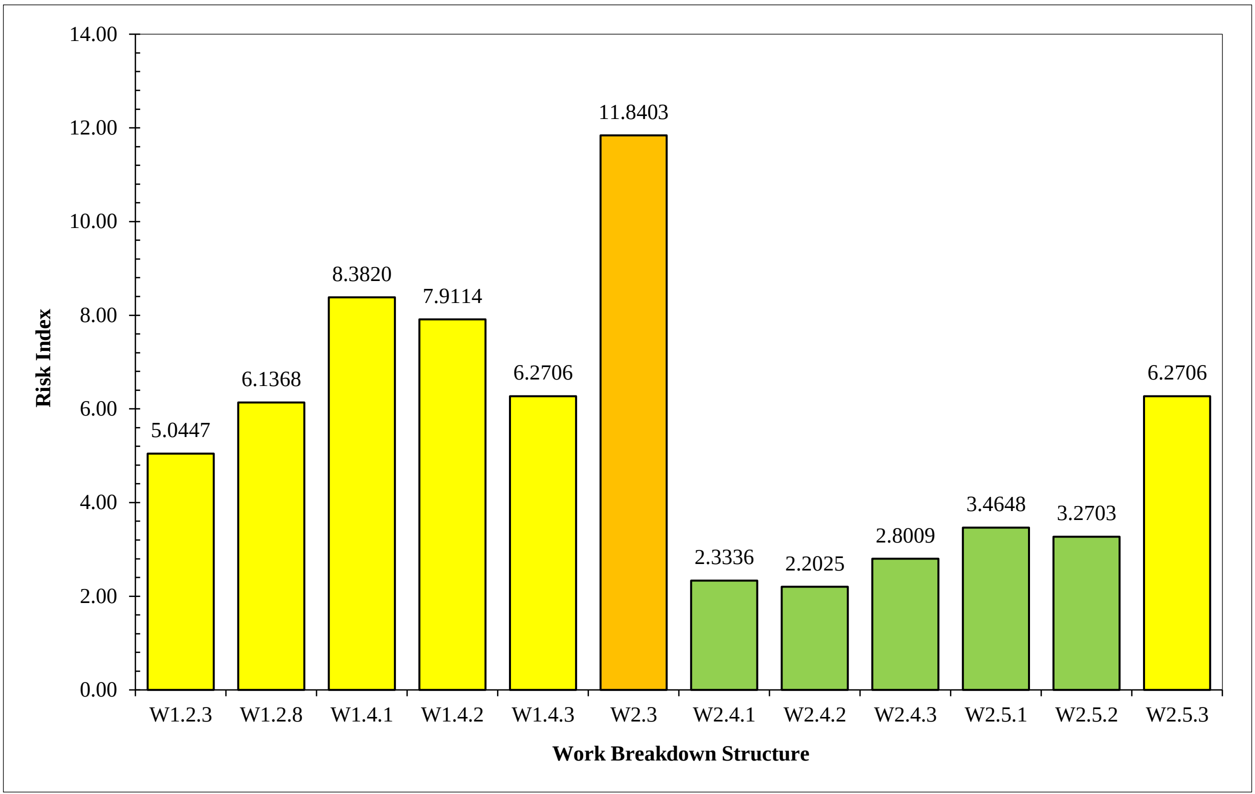

Figure 6. Risk Index analysis of Rating on RBS worker fall (R1.6)

The integration of the WBS and RBS in the preceding phases demonstrates the subordinate units of both frameworks. The AHP-rating computations for the corresponding WBS and RBS can produce the risk index for each phase of WBS or the RBS risk at each WBS phase. The substructure comprises moderate-risk categories: W1.1.1:R3.7, with a risk index of 5.02; W1.2.3:R1.6, with a risk index of 5.04; W1.2.3:R3.6, with a risk index of 5.97; W1.2.8:R1.6, with a risk index of 6.14; W1.2.8:R1.9, with a risk index of 5.79; W1.4.1:R1.6, with a risk index of 8.38; W1.4.1:R1.10, with a risk index of 5.05; W1.4.1:R3.1, with a risk index of 5.22; W1.4.2:R1.6, with a risk index of 7.91; W1.4.2:R3.2, with a risk index of 7.11; and W1.4.3:R1.6, with a risk index of 6.27. From the RBS perspective, R1.6 presents the most risk relative to other RBS risks and is anticipated to manifest in W1.2.3, W1.2.8, W1.4.1, W1.4.2, and W1.4.3. Moderate-category risks are mostly influenced by human factors, comprising three risks from the human aspect index: R1.6, R1.9, and R1.10. The subsequent material features encompass four risks: R3.1, R3.2, R3.6, and R3.7. The AHP-rating analysis on the integration of the WBS and RBS is presented in Tables 9 and 10.

Table 9. Analysis AHP-Rating on Risk Index on bridge sub structure

		W1																		
		W1.1				W1.2								W1.3				W1.4		
		W1.1.1	W1.1.2	W1.1.3	W1.1.4	W1.2.1	W1.2.2	W1.2.3	W1.2.4	W1.2.5	W1.2.6	W1.2.7	W1.2.8	W1.3.1	W1.3.2	W1.3.3	W1.3.4	W1.4.1	W1.4.2	W1.4.3
R1	R1.1	0	0	0	0	0	0	0	3.06	0	0	0	0	0	0	0	0	0	0	0
	R1.2	0	0	0	0	0	0	0	0	0	0	0	0	0.68	0	0	1.65	0	0	2.98
	R1.3	2.31	1.65	1.94	0	1.26	0	0	0	0	0	0	0	0	2.17	0	0	0	0	0
	R1.4	1.68	1.20	1.42	0.77	0	0.97	1.72	0	0.60	0	0	2.09	0	0	0	1.18	2.86	2.70	2.14
	R1.5	0	0	0	0	1.10	0	0	0	0	0	0	0	0.58	1.89	0	1.42	0	3.23	2.56
	R1.6	0	0	0	0	0	0	5.04	0	0	0	0	6.14	0	0	0	0	8.38	7.91	6.27
	R1.7	0	0	0	0	0	0	0	0	0	0	3.17	0	0	0	0	0	0	0	0
	R1.8	0	0	0	0	0	0	0	4.16	0	0	0	0	0	0	0	0	0	0	0
	R1.9	4.65	3.32	3.92	0.92	0	0	0	0	0	0	4.58	5.79	0	0	0	0	0	0	0
	R1.10	2.97	2.12	2.50	1.36	0	0	0	0	0	0	0	0	0	0	2.64	0	5.05	0	0
	R1.11	0	0	0	0	0	1.20	2.13	0	0	0.61	0	0	0.60	1.96	1.85	0	3.53	3.34	2.64
	R1.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R1.13	0	0	0	0	0	0	0	3.28	0	0	0	0	0	0	0	0	0	0	0
	R1.14	0	0	0	0	0	0	2.59	0	0	0	0	0	0	0	0	1.78	0	0	3.22
	R1.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2.57	0	4.92	0	0
R2	R2.1	0	0	0	0	0	0	0	0	2.26	0	0	0	0	0	0	0	0	0	0
	R2.2	2.08	1.49	1.76	0	0	1.21	2.13	0.85	0	0.61	2.06	2.60	0	0	1.85	1.47	3.55	3.35	2.65
R3	R3.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.22	0	0
	R3.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7.11	0
	R3.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	R3.6	0	0	0	0	0	3.38	5.97	2.38	0	0	0	0	0	0	0	0	0	0	0
	R3.7	5.02	3.59	1.47	0	0	0	0	0	0	0	4.95	0	0	0	0	0	0	0	0

Table 10. Analysis AHP-Rating on Risk Index on bridge super structure

		W2										
		W2.1			W2.2	W2.3	W2.4			W2.5		
		W2.1.1	W2.1.2	W2.1.3			W2.4.1	W2.4.2	W2.4.3	W2.5.1	W2.5.2	W2.5.3
R1	R1.1	0	0	0	0	0	0	0	0	0	0	0
	R1.2	0	0	0.83	0	0	0	0	1.33	0	0	2.98
	R1.3	0	1.03	0.82	2.40	0	1.09	1.03	0	1.62	1.53	2.93
	R1.4	0.80	0.75	0.60	1.75	4.04	0.80	0.75	0.96	1.18	1.12	2.14
	R1.5	0.95	0.90	0.71	0	0	0.95	0.90	1.14	1.41	1.33	2.56
	R1.6	0	0	0	0	11.84	2.33	2.20	2.80	3.46	3.27	6.27
	R1.7	0	0	0	0	0	0	0	0	0	0	0
	R1.8	0	0	0	0	0	0	0	0	0	0	0
	R1.9	0	0	0	0	0	0	0	0	0	0	0
	R1.10	0	0	0	0	0	0	0	0	0	0	0
	R1.11	0	0	0	0	4.99	0.98	0.93	0	1.46	1.38	2.64
	R1.12	0	0	0	1.90	4.39	0	0	0	0	0	0
	R1.13	0	0	0	0	0	0	0	0	0	0	0
	R1.14	0	0	0.90	0	0	0	0	1.44	0	0	3.22
	R1.15	1.37	0	0	0	0	0	0	0	0	0	0
R2	R2.1	0	0	0	0	0	0	0	0	0	0	0
	R2.2	0.99	0.93	0.74	2.17	5.01	0.99	0.93	1.19	1.47	1.38	2.65
R3	R3.1	0	0	0	0	0	0	0	0	0	0	0
	R3.2	0	1.98	0	0	0	0	1.98	0	0	2.94	0
	R3.3	0	0	0	2.20	5.09	0	0	0	0	0	0
	R3.4	0	0	0	2.21	5.10	0	0	0	0	0	0
	R3.5	0	0	0	0	15.80	0	0	0	0	0	0
	R3.6	0	0	0	0	0	0	0	0	0	0	0
	R3.7	0	0	0	0	0	0	0	0	0	0	0

The AHP-rating analysis results for the integration of the WBS and RBS for the superstructure indicate that high-risk activities are located in W2.3:R1.6, with a risk index of 11.84, and W2.3:R3.5, with a risk index of 15.80. Medium-risk activities are identified in W2.3:R2.2, with a risk index of 5.01; W2.3:R3.3, with a risk index of 5.09; W2.3:R3.4, with a risk index of 5.10; and W2.5.3:R1.6, with a risk index of 6.27. The highest RBS risk is found in R3.5 in task WBS2.3, followed by R1.6 in task W2.3. Other risks in the medium category include R1.6 in task W2.3.5, R2.2 in task W2.3, R3.3 in task W2.3, and R3.4 in task W2.3. Within the RBS risk superstructure, R1.6 is in the high and medium categories, R2.2 is in the medium category, R3.3 is in the medium category, R3.4 is in the medium category, and R3.5 is in the high category.

Project managers can systematically identify and assess risks by using an idealized WBS-RBS rating system in bridge construction as the basis for assessing risks. This approach quantifies risks by assigning probability and severity ratings, which improves project safety and, more importantly, decision-making. The scores of risks can be used to prioritize risks so that management efforts can be focused on achieving timely project completion and effective resource allocation. A robust framework for risk management in bridge construction projects is proposed by integrating WBS-RBS with AHP ratings through an idealized method. With this approach, critical risks are identified early and prioritized effectively; thus, the project outcomes in terms of safety, cost control, and due dates are increased. When this structured methodology is applied to all work packages in the RBS, project managers can develop specific mitigation strategies that will contribute to the overall project success while preventing delays or cost overruns.

4.6. Discussion

Bridge building should include thorough risk identification, so engineers can understand the possible dangers involved. The WBS organizes the many work stages in bridge construction; the RBS groups potential risks. The combination of the WBS and RBS helps engineers understand the scope of potential hazards at each work phase and the magnitude of the risks (risk index). An effective instrument for detecting and analyzing safety concerns in bridge construction projects is the WBS-RBS method. This method allows a detailed and systematic evaluation of hazards, addressing the complex and nebulous aspects of bridge building. The WBS-RBS matrix is highly effective in comprehensively identifying the indicator system for safety risk analysis in urban elevated bridge building [45].

The integration of the WBS and RBS can identify bridge construction safety risks in an effective way. It permits the systematic analysis of potential hazards at different stages of the construction process. Risks have been identified with the WBS-RBS method during different phases of large bridge construction. These structures can be coupled to link risks to specific construction activities and to systematically analyze risks [10, 79]. Similar to Li et al. [79], WBS-RBS can be used in creating a risk decomposition matrix to identify high-risk activities in bridge construction; it can also be used for systematic and thorough risk assessment, as it can prioritize the risk variables and provide direction concerning how to formulate targeted safety measures [35, 39].

The combined use of the WBS and RBS in this work enhances both scope management and risk management. While the WBS concerns itself with breaking the project into deliverables and tasks that can be managed, the RBS seeks the categorization of potential risks to correctly identify, assess, and mitigate them. In terms of the levels of the WBS, it is broken down into three levels, including two tasks on level 1, 8 tasks on level 2, and 30 tasks on level 3, and there are two potential risks on level 1 and 24 potential risks on level 2 for the RBS. Likewise, Rianty et al. [80] propose a risk-based WBS for quality planning for building projects by introducing five main hierarchies and two supplementary hierarchies of 14 dominant risk areas for quality performance. Combining the WBS and RBS offers a defined technique for risk identification, evaluation, and mitigation in numerous phases of the project. The approach has been used successfully in various domains, such as dam construction [81], electric vehicle safety [35], and several others. Moreover, Jeong & Jeong [82] also used the WBS-RBS method to classify hazard hierarchies in the construction industry, with four levels of the WBS and an RBS up to level 5.

The WBS modelling and RBS modelling are then joined together through a coupling matrix that defines the relationship between the WBS and RBS. Overall, this research combines the WBS and RBS to provide complete risk factor identification for the specific work packages. Using the WBS-RBS coupling matrix, Chen et al. [35] were able to identify the risks, analyze the vehicle fire risk, and obtain 15 risk factors across four vehicle systems. The integrated WBS and RBS method provides a unique risk identification, analysis, and mitigation framework for construction projects. Since project managers are breaking down work activities and the associated risks into hierarchical structures, they can design a better way of developing safety plans and also perform proper project resource allocation, reducing the occurrence of accidents on the construction site [38, 81].

The bridge construction work is done through a synthesis of the WBS, RBS, and AHP. Safety in bridge building has been assessed using the AHP. This research applies the AHP to perform the assessment and prioritization of safety factors in bridge construction projects. The rating method is used to evaluate the WBS weighting and the priorities in the AHP to rank the risk magnitude at each phase of the WBS. A safety risk evaluation model of bridge construction is formulated using the AHP in Wu et al. [63], and critical factors affecting bridge-building safety are identified [4, 63].

The AHP has been found to be a versatile and powerful tool to evaluate bridge-building safety concerns. According to this qualitative interpretation of decision-making, the complex decision-maker (manager) can assess a portfolio of actions, the risk occurrence likelihood, the expected outcome, and an expert's viewpoint [83].

The analysis results show that the risk of girder falls during erection (R3.5) poses the greatest risk in bridge construction and occurs during the girder and diaphragm installation phase (W2.3). Accidents caused by falling girders are the main cause of bridge construction accidents in Indonesia. Bridge construction accidents in Indonesia are caused by a lack of awareness and knowledge of occupational safety. Safety aspects are often not a priority in project management and are not well understood in terms of why workplace safety regulations are enforced [2]. Unsafe acts resulting from this account for 61% of construction accidents [84]. Unsafe working conditions contribute to 39% of the high accident rate [84]. Additionally, construction machinery is the second largest cause of accidents (36% of accidents are collisions with heavy equipment) [85], specifically in high-risk lifting and moving tasks [85]. In order to reduce accidents in bridge construction in Indonesia, it is essential to improve the awareness of work safety, enforce strict laws, and use the correct standard operating procedure (SOP), as well as make sure the vehicle used to construct the bridge is appropriate [2, 85]. It is also very important to seriously implement occupational safety regulations in an infrastructure project, and all stakeholders must be committed to this [2].

The analysis results rank the risk of a worker falling (R1.6) during girder and diaphragm installation activities (W2.3) as high. Falling from a height can be prevented by following safety precautions and programs. Workplace falls from a height are caused by the height of the workplace, and there are more work accidents in general due to the height of the workplace. The risk of falling from a height is high [12, 61, 86–88], and unsafe behavior in the workplace is the main cause of workplace accidents, including workers falling. Noncompliance with the use of PPE [89] is one form of this. In addition to causing behaviors that are unsafe and increasing the risk of workplace accidents, it can increase the risk of falling when working at a height if PPE is not used and the worker is not compliant [90, 91]. It is necessary to increase the awareness of adopting an effective hazard reporting system, such as by completing a hazard observation card [92, 93], and preventing workplace accidents, such as accidents due to workers falling, which can be prevented by using PPE.

5. Conclusion

This study was conducted to identify and analyze safety in concrete bridge construction. Risk identification was performed by using the WBS to obtain work stages, and three levels of the WBS for the stages of concrete bridge construction work were obtained. Bridge construction work is divided into substructure work and superstructure work, with the substructure consisting of the earthwork, foundation, pile cap, and pier, while the superstructure consists of girder fabrication, girder storage, the installation of girders and diaphragms, the installation of the bridge main deck, and the installation of parapets. The last level represents the sub-work from the previous level. The identified risks consist of 24 activities divided into two levels, where the first level consists of three aspects, namely the human, equipment, and material aspects. The human aspect consists of 15 risks, the equipment aspect consists of 2 risks, and the material aspect consists of 7 risks. The integration of the WBS and RBS in the form of a dynamic matrix obtains the relationship between the stages of work in the WBS and the potential risk activities (RBS) at each stage of the work.

Risk assessment is conducted by competent respondents on the WBS and RBS; then, they are analyzed to obtain a risk index for each WBS and RBS factor. The index for the WBS is analyzed with the AHP to obtain priorities related to the risky activities in the RBS. To obtain a comparable numerical scale for the RBS, the WBS is analyzed using the rating method; this rating scale is used to analyze the magnitude of the RBS risk related to each WBS. The highest worker fall risk index is at the girder and diaphragm installation activities stage, followed by pier reinforcement and pier formwork, and in the next sequence, 12 work activities can be seen in the WBS. The risk index for the RBS related to the WBS is analyzed so that information is obtained on the magnitude of the RBS risk that may occur for the relevant WBS task. This information on the magnitude of the risk is important for contractors, so that during the implementation of each stage of work, accurate information can be obtained regarding the potential risks that may occur and an appropriate response can be planned.

6. Declarations

6.1. Author Contributions

Conceptualization, W.H.; methodology, W.H.; software, W.H.; validation, W.H., S.A.K., and D.H.; formal analysis, W.H.; investigation, W.H.; resources, W.H.; data curation, W.H.; writing—original draft preparation, W.H.; writing—review and editing, W.H., S.A.K., and D.H.; visualization, W.H.; supervision, S.A.K., D.H., and W.S.; project administration, W.H.; funding acquisition, W.H. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The funding provider for this research is Sebelas Maret University through Doctoral Dissertation Research Grant (Hibah PDD) contract number 260/UN27.22/HK.07.00/2021 and 254/UN27.22/PT.01.03/2022.

6.4. Acknowledgements

I extend my sincere gratitude to Sebelas Maret University for financing this research and to the students who contributed to the interview and data collection procedure.

6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Latupeirissa, J. E., Wong, I. L. K., & Tiyow, H. C. P. (2021). Causes of work accidents and its impact on the road and bridge construction projects. IOP Conference Series: Earth and Environmental Science, 907(1), 12023. doi:10.1088/1755-1315/907/1/012023.

[2] Mairizal, Edrizal, Ismail, M., & Mohamad Zin, R. (2019). Identifying occurrences of accident at work place in terms of occupational safety on roads and bridges infrastructure in Indonesia. IOP Conference Series: Materials Science and Engineering, 513(1), 12040. doi:10.1088/1757-899X/513/1/012040.

[3] Yu, W., Cui, F., & Cao, X. (2023). Safety monitoring of large cantilever bridge construction based on multi-source data measurement. Fourth International Conference on Geoscience and Remote Sensing Mapping (GRSM 2022), 72. doi:10.1117/12.2668197.

[4] Shan, Z., Qiu, L., Chen, H., & Zhou, J. (2023). Coupled Analysis of Safety Risks in Bridge Construction Based on N-K Model and SNA. Buildings, 13(9), 2178. doi:10.3390/buildings13092178.

[5] Joshi, H. P., & Adhikari, C. R. (2024). Status of Construction Safety in Local Road Bridge Construction and its Consequences in Project Implementation: A Study in Gandaki Province, Nepal. Journal of Engineering Technology and Planning, 5(1), 84–97. doi:10.3126/joetp.v5i1.69725.

[6] Xu, Z., Zhang, X., Xie, H., Chen, B., Li, Z., & Zhang, Y. (2023). Deformation Monitoring and Sensitivity Analysis of Under-Construction Bridges Considering Ps Optimization. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives, 48(1/W2-2023), 1289–1295. doi:10.5194/isprs-archives-XLVIII-1-W2-2023-1289-2023.

[7] Hartono, W., Purnomo, A. P. H., & Sunarmasto. (2023). Risk Allocation Implementation Analysis of Public-Private Partnership for Infrastructure Project (Case Study of the Solo-Yogyakarta-NYIA Kulon Progo Highway Project). Lecture Notes in Civil Engineering, 225, 853–862. doi:10.1007/978-981-16-9348-9_76.

[8] Feronica Damanik, M., Latief, Y., & Nugroho, D. B. (2023). Analysis of Relation Between Risk-Based Work Breakdown Structure (WBS) on Integrated Design and Construction Works of Design and Build Contract on Mechanical and Electrical Works of High Rise Building for Improving Safety Performance. International Journal of Science, Technology & Management, 4(4), 872–877. doi:10.46729/ijstm.v4i4.860.

[9] Damanik, M. F., Latief, Y., & Nugroho, D. B. (2023). Development of Risk-based Work Breakdown Structure (WBS) Standards for Integrated Design and Construction Phase on Design-Build Contract of Mechanical and Electrical Works of High-Rise Building to Improve Construction Safety Performance. International Journal of Engineering Trends and Technology, 71(8), 119–130. doi:10.14445/22315381/IJETT-V71I8P210.

[10] Ran, R., Wang, S., Fang, J., & Wang, Y. (2024). Safety Risk Analysis of Urban Viaduct Construction Based on Dynamic Weight. Buildings, 14(4), 1014. doi:10.3390/buildings14041014.

[11] Bhattacharjee, K., Bugalia, N., & Mahalingam, A. (2024). An analysis of safety practices for small, medium, and large construction projects: A resilience engineering perspective. Safety Science, 169, 106330. doi:10.1016/j.ssci.2023.106330.

[12] Hartono, W., Handayani, D., & Rhamadani, H. C. (2024). Analysis the Effect of Height on Work Accidents in High Rise Building Projects. E3S Web of Conferences, 517. doi:10.1051/e3sconf/202451705028.

[13] Manikandan, J. (2023). Leveraging Technology in Advancing Construction Workers Safety. Recent Research Reviews Journal, 2(2), 435–445. doi:10.36548/rrrj.2023.2.015.

[14] Elrifaee, M., Zayed, T., Ali, E., & Ali, A. H. (2024). IoT Contributions to The Safety of Construction Sites: A Comprehensive Review of Recent Advances, Limitations, and Suggestions for Future Directions. Internet of Things, 101387. doi:10.1016/j.iot.2024.101387.

[15] Hashmi, F., Hassan, M. U., Zubair, M. U., Ahmed, K., Aziz, T., & Choudhry, R. M. (2024). Near-Miss Detection Metrics: An Approach to Enable Sensing Technologies for Proactive Construction Safety Management. Buildings, 14(4). doi:10.3390/buildings14041005.

[16] Lin, S. S., Zhou, A., & Shen, S. L. (2024). Multi-status Bayesian network for analyzing collapse risk of excavation construction. Automation in Construction, 158, 105193. doi:10.1016/j.autcon.2023.105193.

[17] Ma, Z., & Chen, Z. S. (2024). Mining construction accident reports via unsupervised NLP and Accimap for systemic risk analysis. Automation in Construction, 161, 105343. doi:10.1016/j.autcon.2024.105343.

[18] Asfandiyar, & Cheema, S.M. (2023). Relationship among Safety, Quality and Productivity in Construction Projects. Journal of Development and Social Sciences, 4(I). doi:10.47205/jdss.2023(4-i)17.

[19] Khairudin, A. H., Abas, N. H., & Kariya, N. (2021). The Practices of Occupational Safety and Health Management in Construction Industry: Case Studies of High Rise Building Projects. Journal of Structural Monitoring and Built Environment, 1(1), 2. doi:10.30880/jsmbe.2021.01.01.002.

[20] Saha, S., Chattaraj, S., Sarkar, S., & Maji, R. (2024). Importance Of Effective Strategies for Workplace Safety Issues in Construction Sites. Futuristic Trends in Artificial Intelligence Volume 3 Book 5, 137–147, IIP Series, Chikkamagaluru, India. doi:10.58532/v3bbai5p3ch1.

[21] Junjia, Y., Alias, A. H., Haron, N. A., & Abu Bakar, N. (2024). Identification and analysis of hoisting safety risk factors for IBS construction based on the AcciMap and cases study. Heliyon, 10(1), 23587. doi:10.1016/j.heliyon.2023.e23587.

[22] Rasouli, S., Alipouri, Y., & Chamanzad, S. (2024). Smart Personal Protective Equipment (PPE) for construction safety: A literature review. Safety Science, 170, 106368. doi:10.1016/j.ssci.2023.106368.

[23] Kulinan, A. S., Park, M., Aung, P. P. W., Cha, G., & Park, S. (2024). Advancing construction site workforce safety monitoring through BIM and computer vision integration. Automation in Construction, 158, 105227. doi:10.1016/j.autcon.2023.105227.

[24] Newaz, M. T., Ershadi, M., Jefferies, M., & Davis, P. (2024). A critical review of the feasibility of emerging technologies for improving safety behavior on construction sites. Journal of Safety Research, 89, 269–287. doi:10.1016/j.jsr.2024.04.006.

[25] Zhao, X. (2024). Construction risk management research: intellectual structure and emerging themes. International Journal of Construction Management, 24(5), 540–550. doi:10.1080/15623599.2023.2167303.

[26] Khumpaisal, S. (2018). Risks in the Construction Project Procurement Process and the Mitigation Methods. Journal of Architectural/Planning Research and Studies (JARS), 5(2), 133–146. doi:10.56261/jars.v5i2.169168.

[27] Priyadarshini, L., & Roy, P. (2022). Risk Assessment and Management in Construction Industry. Recent Developments in Sustainable Infrastructure (ICRDSI-2020)—Structure and Construction Management. Lecture Notes in Civil Engineering, vol 221. Springer, Singapore. doi:10.1007/978-981-16-8433-3_46.

[28] Pahilajrai, W. D. (2021). Analysis of Risk Management in Construction Projects Using SPSS method. Recent Trends in Management and Commerce, 2(4), 153–162. doi:10.46632/rmc/2/4/22.

[29] Jibril, A., & Shaban, B. A. (2021). Risk management in construction projects in Somalia. International Journal of Advanced Engineering, Sciences and Applications, 2(2), 38–41. doi:10.47346/ijaesa.v2i2.70.

[30] Odimabo, O., & Oduoza, C. F. (2018). Guidelines to Aid Project Managers in Conceptualising and Implementing Risk Management in Building Projects. Procedia Manufacturing, 17, 515–522. doi:10.1016/j.promfg.2018.10.091.

[31] Kermanimoghaddam, A. (2023). Investigating the risk of international construction projects using artificial-fuzzy neural networks technique. Technium Sustainability, 3, 36–40. doi:10.47577/sustainability.v3i.8603.

[32] Luo, Q., Sun, C., Li, Y., Qi, Z., & Zhang, G. (2024). Applications of digital twin technology in construction safety risk management: a literature review. Engineering, Construction and Architectural Management, 3(3). doi:10.1108/ECAM-11-2023-1095.

[33] Wu, Y., & Lu, P. (2022). Comparative Analysis and Evaluation of Bridge Construction Risk with Multiple Intelligent Algorithms. Mathematical Problems in Engineering, 2022, 1–12. doi:10.1155/2022/2638273.

[34] Wu, Y., Wang, Y., Liu, H., Xie, L., Jiao, L., & Lu, P. (2024). Risk assessment of bridge construction investigated using random forest algorithm. Scientific Reports, 14(1), 20964. doi:10.1038/s41598-024-72051-5.

[35] Chen, J., Li, K., & Yang, S. (2022). Electric Vehicle Fire Risk Assessment Based on WBS-RBS and Fuzzy BN Coupling. Mathematics, 10(20), 3799. doi:10.3390/math10203799.

[36] Yan, H., Gao, C., Elzarka, H., Mostafa, K., & Tang, W. (2019). Risk assessment for construction of urban rail transit projects. Safety Science, 118, 583–594. doi:10.1016/j.ssci.2019.05.042.

[37] Zhang, L. W., & Zhao, Y. G. (2024). Linear Moments-Based Monte Carlo Simulation for Reliability Analysis with Unknown Probability Distributions. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering, 10(2). doi:10.1115/1.4064702.

[38] Cai, X., Huang, J., & Peng, C. (2023). Research on Construction Workers' Safety Risk Sharing in Tunneling Projects Based on a Two-Mode Network: A Case Study of the Shangwu Tunnel. Buildings, 13(11), 2689. doi:10.3390/buildings13112689.

[39] Yan, K., Jin, L., & Yu, X. (2024). Ordered weighted evaluation method of lifting operation safety risks considering coupling effect. Scientific Reports, 14(1), 5776. doi:10.1038/s41598-024-56039-9.

[40] Fu, T., Shi, K., Shi, R., Lu, Z., & Zhang, J. (2024). Risk Assessment of TBM Construction Based on a Matter-Element Extension Model with Optimized Weight Distribution. Applied Sciences (Switzerland), 14(13), 5911. doi:10.3390/app14135911.

[41] Moon, H., Mirmotalebi, S., Jang, Y., Ahn, Y., & Kwon, N. (2024). Risk Evaluation of Radioactive Concrete Structure Decommissioning in Nuclear Power Plants Using Fuzzy-AHP. Buildings, 14(6), 1–23. doi:10.3390/buildings14061536.

[42] Saraswati, N. N., Juliastuti, Haripriambodo, T., & Kesuma, L. M. (2023). The analysis of cofferdam construction based on risk assessment using HIRARC and FMEA methods. IOP Conference Series: Earth and Environmental Science, 1169(1), 12023. doi:10.1088/1755-1315/1169/1/012023.

[43] Güney, G., & Kahraman, B. (2022). Implementation of the analytic hierarchy process (AHP) and Fine–Kinney method (FKM) against risk factors to determine the total cost of occupational health and safety precautions in environmental research laboratories. International Journal of Occupational Safety and Ergonomics, 28(4), 2606–2622. doi:10.1080/10803548.2021.2010969.

[44] Qiu, C., & Li, X. (2023). Blended Analysis of Occupational Safety Hazards and Risk Assessment Approach in the Construction Industry. Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021. CSCE 2021. Lecture Notes in Civil Engineering, vol 251. Springer, Singapore. doi:10.1007/978-981-19-1029-6_38.

[45] Qiu, C., & Li, X. (2022). Blended analysis of occupational safety hazards and digital transformation of risk assessment in construction industries. Canadian Journal of Civil Engineering, 50(3), 184–196. doi:10.1139/cjce-2022-0036.

[46] Zhang, S., Yu, B., Li, R., & Wan, Y. (2024). Research on the Intelligent Construction and Development of Bridge Engineering Safety Management. E3S Web of Conferences, 565, 3013. doi:10.1051/e3sconf/202456503013.

[47] Li, G., Ran, R., Fang, J., Peng, H., & Wang, S. (2021). Early warning for the construction safety risk of bridge projects using a RS-SSA-LSSVM model. Advances in Civil Engineering, 2021. doi:10.1155/2021/4449451.

[48] Yuan, H., Zhang, W., & You, J. (2018). Assessment of Bridge Construction Safety Risk based on Improved Cloud Model. Journal of Engineering Studies, 10(06), 600–606. doi:10.3724/sp.j.1224.2018.00600.

[49] Albrechtsen, E., Solberg, I., & Svensli, E. (2019). The application and benefits of job safety analysis. Safety Science, 113, 425–437. doi:10.1016/j.ssci.2018.12.007.

[50] Chen, Q., Long, D., Yang, C., & Xu, H. (2023). Knowledge Graph Improved Dynamic Risk Analysis Method for Behavior-Based Safety Management on a Construction Site. Journal of Management in Engineering, 39(4), 5306. doi:10.1061/jmenea.meeng-5306.

[51] Yang, Y. (2024). Safety Risk Assessment Analysis of Bridge Construction Using Backpropagation Neural Network. Journal of Architectural Research and Development, 8(2), 24–30. doi:10.26689/jard.v8i2.6386.

[52] Jian, S. (2020). The application of BIM technology in road and bridge construction management. IOP Conference Series: Earth and Environmental Science, 587(1), 12002. doi:10.1088/1755-1315/587/1/012002.

[53] Liu, W., Liu, F., Fang, W., & Love, P. E. D. (2024). Causal discovery and reasoning for geotechnical risk analysis. Reliability Engineering & System Safety, 241, 109659. doi:10.1016/j.ress.2023.109659.

[54] Hai, N., Gong, D., & Dai, Z. (2024). Target spectrum-based risk analysis model for utility tunnel O&M in multiple scenarios and its application. Reliability Engineering & System Safety, 242, 109777. doi:10.1016/j.ress.2023.109777.

[55] Zhang, P., Zhang, Z. J., & Gong, D. Q. (2024). An improved failure mode and effect analysis method for group decision-making in utility tunnels construction project risk evaluation. Reliability Engineering & System Safety, 244, 109943. doi:10.1016/j.ress.2024.109943.

[56] Zio, E., & Miqueles, L. (2024). Digital twins in safety analysis, risk assessment and emergency management. Reliability Engineering & System Safety, 246, 110040. doi:10.1016/j.ress.2024.110040.

[57] Musarat, M. A., Alaloul, W. S., Zainuddin, S. M. B., Qureshi, A. H., & Maqsoom, A. (2024). Digitalization in Malaysian construction industry: Awareness, challenges and opportunities. Results in Engineering, 21, 102013. doi:10.1016/j.rineng.2024.102013.

[58] Yang, C., Wang, Q., Wei, R., & Lu, K. (2018). Research on FAHP Method Based on Highway Bridge Safety. Engineering, 10(06), 336–344. doi:10.4236/eng.2018.106024.

[59] Li, Q., Lei, J., & Zhang, H. (2020). Risk estimation of large complex bridge construction based on factor analysis. E3S Web of Conferences, 218, 4011. doi:10.1051/e3sconf/202021804011.

[60] Sobieraj, J., & Metelski, D. (2022). Project Risk in the Context of Construction Schedules—Combined Monte Carlo Simulation and Time at Risk (TaR) Approach: Insights from the Fort Bema Housing Estate Complex. Applied Sciences (Switzerland), 12(3), 1044. doi:10.3390/app12031044.

[61] Tsair Chang, J., & Hsiao, H. C. (2019). Analytic Hierarchy Process for Evaluation Weights on Occupational Safety and Hygiene Items in the Bridge Construction Site. IOP Conference Series: Earth and Environmental Science, 233(3), 32031. doi:10.1088/1755-1315/233/3/032031.

[62] Gunduz, M., & Alfar, M. (2019). Integration of innovation through analytical hierarchy process (Ahp) in project management and planning. Technological and Economic Development of Economy, 25(2), 258–276. doi:10.3846/tede.2019.8063.

[63] Wu, C., Yan, Y., Yang, S., Huang, Y., Ren, X., Wu, H., Dong, E., & Zhu, S. (2021). Research on safety risk evaluation model of bridge construction based on analytic hierarchy process. Journal of Physics: Conference Series, 2005(1). doi:10.1088/1742-6596/2005/1/012183.

[64] Su, H., Guo, C., Wang, Z., Han, T., Kamanda, D. B., Su, F., & Shang, L. (2024). Research on safety condition assessment methodology for single tower steel box girder suspension bridges over the sea based on improved AHP-fuzzy comprehensive evaluation. Scientific Reports, 14(1), 1–21. doi:10.1038/s41598-024-61579-1.

[65] Koohathongsumrit, N., & Meethom, W. (2024). Risk analysis in underground tunnel construction with tunnel boring machines using the Best–Worst method and data envelopment analysis. Heliyon, 10(1), 23486. doi:10.1016/j.heliyon.2023.e23486.

[66] Hwang, S., & Choi, M. (2024). Integrative building safety evaluation to mitigate disaster risks: a case study on public-use buildings in Seoul. Journal of Asian Architecture and Building Engineering, 1–15. doi:10.1080/13467581.2024.2329360.

[67] Bayhun, S., & Demirel, N. Ç. (2024). Hazard Identification and Risk Assessment for Sustainable Shipyard Floating Dock Operations: An Integrated Spherical Fuzzy Analytical Hierarchy Process and Fuzzy CoCoSo Approach. Sustainability (Switzerland) , 16(13). doi:10.3390/su16135790.

[68] Cheng, F., & Liu, Y. (2021). Evaluation of risk for construction safety of fabricated buildings based on analytic hierarchy process. IOP Conference Series: Earth and Environmental Science, 791(1), 8–13. doi:10.1088/1755-1315/791/1/012063.

[69] Huang, Z., Zhao, W., Zhang, Y., Yao, X., Jia, Q., Wang, H., Le, T., Song, D., & Gao, Y. (2020). Comprehensive Safety Evaluation of Emergency Training for Building Ruins Scenario Based on Analytic Hierarchy Process-Grey Fuzzy Evaluation. IEEE Access, 8, 147776–147789. doi:10.1109/ACCESS.2020.3015829.

[70] Darko, A., Chan, A. P. C., Ameyaw, E. E., Owusu, E. K., Pärn, E., & Edwards, D. J. (2019). Review of application of analytic hierarchy process (AHP) in construction. International Journal of Construction Management, 19(5), 436–452. doi:10.1080/15623599.2018.1452098.

[71] Du, M., & Han, T. (2021). Research on Construction Engineering Safety Management. Foreign Language Science and Technology Journal Database Engineering Technology, 507852. doi:10.47939/et.v2i11.04.

[72] Yang, Y., Chen, Y., & Tang, Z. (2021). Analysis of the safety factors of municipal road undercrossing existing bridge based on fuzzy analytic hierarchy process methods. Transportation Research Record, 2675(12), 915–928. doi:10.1177/03611981211031887.

[73] Zhang, Q., Song, Y., & Shi, J. (2021). Network Model and Analysis of Construction Project Safety Risk and Stakeholder Based on SNA. Proceedings of the 2021 International Conference on Social Sciences and Big Data Application (ICSSBDA 2021), 614, 249–260. doi:10.2991/assehr.k.211216.047.

[74] Cerezo-Narváez, A., Pastor-Fernández, A., Otero-Mateo, M., & Ballesteros-Pérez, P. (2020). Integration of cost and work breakdown structures in the management of construction projects. Applied Sciences (Switzerland), 10(4), 1–33. doi:10.3390/app10041386.

[75] Aydın, M. C., Sevgi Birincioğlu, E., Büyüksaraç, A., & Işık, E. (2024). Earthquake Risk Assessment Using GIS-Based Analytical Hierarchy Process (AHP): The Case of Bitlis Province (Türkiye). International Journal of Environment and Geoinformatics, 11(1), 1–9. doi:10.30897/ijegeo.1306580.

[76] Rodrigues de Oliveira, B., & Duarte, M. A. Q. (2024). Automatic and Semi-automatic Analytic Hierarchy Process (AHP). Trends in Agricultural and Environmental Sciences, e240009. doi:10.46420/taes.e240009.

[77] Liang, B., Zhang, S., Li, D., Zhai, Y., Wang, F., Shi, L., & Wang, Y. (2021). Safety Risk Evaluation of Construction Site Based on Unascertained Measure and Analytic Hierarchy Process. Discrete Dynamics in Nature and Society, 2021, 1–14. doi:10.1155/2021/7172938.

[78] Bilașco, Ștefan, & Man, T. C. (2024). GIS-Based Spatial Analysis Model for Assessing Impact and Cumulative Risk in Road Traffic Accidents via Analytic Hierarchy Process (AHP)—Case Study: Romania. Applied Sciences (Switzerland), 14(6), 2643. doi:10.3390/app14062643.

[79] Li, Q., Qian, H., Pei, J., Wang, S., & Lei, J. (2020). Safety Risk Analysis of Bridge Rhombic Hanging Basket Construction Based on WBS-RBS and Rough Set Theory. IOP Conference Series: Materials Science and Engineering, 780(7), 72033. doi:10.1088/1757-899X/780/7/072033.

[80] Rianty, M., Latief, Y., & Riantini, L. S. (2018). Development of risk-based standardized WBS (Work Breakdown Structure) for quality planning of high rise building architectural works. MATEC Web of Conferences, 159. doi:10.1051/matecconf/201815901019.

[81] Hidayah, D. N., Latief, Y., & Riantini, L. S. (2018). Development of work breakdown structure standard based on risk for safety planning on dam construction work. IOP Conference Series: Materials Science and Engineering, 420(1), 012003. doi:10.1088/1757-899X/420/1/012003.

[82] Jeong, J., & Jeong, J. (2021). Novel approach of the integrated work & risk breakdown structure for identifying the hierarchy of fatal incident in construction industry. Journal of Building Engineering, 41, 102406. doi:10.1016/j.jobe.2021.102406.

[83] P Asrani, N., Venkatasubramanian, C., Muthu, D., S, P., & Ramakrishnan, K. (2018). Risk Management – Decision Making Using Analytical Hierarchy Process. International Journal of Engineering & Technology, 7(3.12), 188. doi:10.14419/ijet.v7i3.12.15917.

[84] Ghuzdewan, T., & Damanik, P. (2019). Analysis of accident in Indonesian construction projects. MATEC Web of Conferences, 258, 02021. doi:10.1051/matecconf/201925802021.

[85] Bria, T. A., Chen, W. T., Muhammad, M., & Rantelembang, M. B. (2024). Analysis of Fatal Construction Accidents in Indonesia—A Case Study. Buildings, 14(4), 1010. doi:10.3390/buildings14041010.

[86] Ajith, S., Sivapragasam, C., & Arumugaprabu, V. (2019). Analysis on constructional hazards, risk assessment techniques and safety helmets in construction sites. AIP Conference Proceedings, 2128, 50013. doi:10.1063/1.5117985.

[87] Chen, T.-T., & Wang, C. C. (2014). Falling Risk Assessment of Advanced Shoring Method Bridge Construction Projects. Design, Construction, and Maintenance of Bridges, 14–21. doi:10.1061/9780784478516.002.

[88] Chen, T. T., & Wang, C. H. (2017). Fall risk assessment of bridge construction using Bayesian network transferring from fault tree analysis. Journal of Civil Engineering and Management, 23(2), 273–282. doi:10.3846/13923730.2015.1068841.

[89] Nugraha, K. O. P. P., & Rifai, A. P. (2023). Convolutional Neural Network for Identification of Personal Protective Equipment Usage Compliance in Manufacturing Laboratory. Jurnal Ilmiah Teknik Industri, 22(1), 11–24. doi:10.23917/jiti.v22i1.21826.

[90] Guo, S., He, J., Li, J., & Tang, B. (2020). Exploring the impact of unsafe behaviors on building construction accidents using a Bayesian network. International Journal of Environmental Research and Public Health, 17(1), 221. doi:10.3390/ijerph17010221.

[91] Dodoo, J. E., & Al-Samarraie, H. (2019). Factors leading to unsafe behavior in the twenty first century workplace: a review. Management Review Quarterly, 69(4), 391–414. doi:10.1007/s11301-019-00157-6.

[92] Mika, F., & Dunger, D. (2018). Observations of employees - a condition for improving the culture of safety at work. Sigurnost, 60(3), 261–266. doi:10.31306/s.60.3.1. (In Bosnian).

[93] Paramitha, P. E. (2021). Digitalizing and Geo-Enabling Observation Cards to Improve Hazard Mitigation and Better Risk Assessment. Proc of the Indonesian Petroleum Association 44th Annual Convention and Exhibition, IPA21-O-208. doi:10.29118/ipa21-o-208.