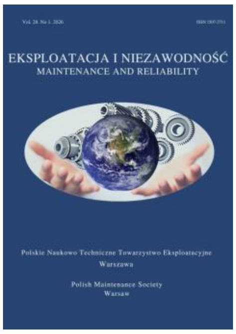

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Risk Assessment of Highway Engineering Construction Safety Reliability Based on Two-Dimensional Cloud Model-Bayesian Network

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Highlights

- Proposing a risk assessment method combining the 2D cloud model and Bayesian network.
- Constructing a fault tree model for risk and 2D comprehensive cloud risk model.
- Bi-directional inference is performed by the Bayesian network.

Abstract

Addressing the challenges of quantifying the fuzziness and randomness in highway engineering construction safety risks using traditional methods, this study proposes a reliability risk assessment approach based on a two-dimensional cloud model and Bayesian network. An indicator evaluation system was constructed to establish the Bayesian network. Based on the Risk Matrix Method, a two-dimensional cloud model was developed. The prior probabilities of risk indicators were calculated, and bidirectional reasoning within the Bayesian network was utilized to solve for the top event probability and identify critical factors. Taking the HB project as a case study, the reliability risk probability was calculated as 0.2933. The top four key risks were identified, and targeted mitigation measures were proposed, thereby validating the model's reliability. The assessment framework established in this study provides an operable quantitative tool for construction safety reliability management through two-dimensional uncertainty quantification and a bidirectional reasoning mechanism.

Keywords

highway engineering, construction safety reliability, two-dimensional cloud model, bayesian network, risk assessment

1. Introduction

In urban and rural transport construction, highway engineering as a critical component of infrastructure construction, its construction safety reliability is directly related to the stable operation of the transport network and the sustainable development of social economy. However, with the increasing complexity of the engineering construction environment and the intensifying market competition, the safety hazards in the construction process are increasing, seriously threatening the reliability of engineering construction. Therefore, conducting risk assessments of the safety and reliability of highway construction, identifying key risk factors, and implementing timely preventive measures are of great significance for ensuring the safety and stability of the construction process and enhancing the reliability of the engineering system.

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In recent years, engineering construction safety risk assessment methods have become a focal point of research for scholars both domestically and internationally. Many studies have focused on exploring scientifically effective risk assessment techniques to improve the safety reliability of engineering construction. For example, Panek et al. [1] applied the Analytic Hierarchy Process (AHP) to solve the decision-making problem of selecting logistics equipment by evaluating key indicators such as efficiency, reliability, and access time. Zhao et al. [2] proposed a standardized method for converting FRAM to Bayesian Network, addressing the issue of insufficient traceability and repeatability in the existing FRAM-BN integration process due to reliance on subjective judgment. Che et al. [3] developed a novel risk analysis method that addresses the issues of indirectness and concealment in traditional FTA when analyzing human errors caused by mental workload overload (MWLOL). Zhang et al. [4] addressed the challenge of insufficient risk quantification in aircraft structural damage risk assessment by combining fatigue crack growth rate and crack detection rate parameters using the Monte Carlo simulation method. Wang [5] proposed a method for construction safety risk management and control using risk quantification assessment. They utilized the LSTM neural network algorithm to achieve risk quantification prediction and developed a system for quantifying assessment and forecasting of safety risks in highway engineering construction. Liu et al. [6] proposed a high-speed railway bridge safety risk assessment model based on the AHP method and BP neural network. This model can comprehensively assess the impact of significant risk factors on high-speed railway bridge construction and predict risk levels consistent with expert review results. Ji et al. [7] proposed a safety risk assessment model for quay crane installation construction based on the CAHP method. By modifying the traditional AHP scale theory and introducing the concept of cloud models, they determined the cloud numerical characteristics of the relative weights of each index and risk values. Finally, the overall assessment results were obtained, and an example analysis was conducted using a container terminal quay crane installation project. The results were consistent with the actual assessment results. Wu [8] summarized the research achievements in safety risk assessment for bridge construction in China and proposed a safety risk assessment system tailored explicitly for constructing large-span steel box girder cable-stayed bridges. Wu et al. [9] proposed a safety risk assessment model for tunnel construction based on the K-Means clustering algorithm. By transforming risk assessment information into a dataset and utilizing the K-Means clustering algorithm to process the dataset, they ultimately determined the risk levels of events, providing decision-making references for tunnel construction risk control. Xu [10] proposed a risk assessment model for tunnel construction based on fuzzy mathematics and expert systems. They developed a tunnel construction safety risk assessment and management expert system based on the JAVA language. Shen and Liu [11] proposed a risk analysis method for deep foundation pit construction based on fuzzy dynamic Bayesian network. They constructed a dynamic evolving FDBN model capable of predicting changes in construction risk probability and identified critical risk factors through sensitivity analysis. Liu et al. [12] proposed a method combining the two-dimensional cloud model and Bayesian network for addressing critical failure modes of non-bonded flexible risers and provided corresponding preventive measures. Zhou [13] proposed a method combining the cloud model and Bayesian network for the dynamic assessment of safety risks in complex systems during shield tunneling under railway crossings. This method effectively evaluates the system's risk level and achieves real-time dynamic safety management through verification using a specific under-railway crossing project. Zhang et al. [14] proposed a method of combining index weights allocation based on binary semantics and established a comprehensive evaluation model. Through case studies, it was demonstrated that this model is practical for long-distance water conveyance tunnel projects. Tan et al. [15] proposed a cloud model-based safety risk assessment method for constructing long-span suspension bridges in mountainous areas with deep valleys. This approach is considered more reasonable and accurate than traditional evaluation methods. Lu et al. [16] proposed a novel method for assessing construction safety risks, aiming to reduce such risks through hazard prevention during the design phase. They also developed a plugin connected to BIM, automatically calculating construction safety risks. Zhang et al. [17] achieved the risk assessment of dam-break floods in the Baoji section of the Qianhe River Basin by adopting the

HEC-RAS model. Yang and Zhao [18] achieved the risk assessment of the safety of the hoisting construction of prefabricated building components by adopting a two-dimensional cloud model with combined weighting. Zhang et al. [19] achieved the seismic resilience assessment of urban systems by adopting a two-dimensional cloud model with an improved subjective weighting method. Wang et al. [20] achieved the risk assessment of the construction of the Yellow River Bridge by adopting a two-dimensional cloud model with combined weighting.

Through referencing a large number of relevant literature, it was found that there is abundant research on construction safety risks, but comparatively less research on the safety reliability of highway engineering construction risks. Therefore, based on the work of many scholars, this paper focuses on the risk assessment of highway engineering construction safety reliability. Considering the complexity of highway engineering construction safety, where multiple stages and factors are involved, there are various potential risks. The two-dimensional cloud model can discretize continuous node states, making it more effective in handling these complex factors and risks. At the same time, Bayesian networks can leverage existing prior knowledge and real-time monitoring data for inference and prediction, effectively enhancing the accuracy and reliability of the assessment results. Therefore, combining the two-dimensional cloud model with Bayesian networks can transform qualitative risk assessment results into quantitative risk values, thereby providing a more concrete way to express and compare the magnitude of different risks. This approach provides strong support for highway engineering construction safety and reliability risk management and decision-making, helping to identify potential risks early, take timely corrective measures, and reduce the possibility of accidents.

2. Risk matrix based on two-dimensional cloud model

2.1. Cloud model theory

The cloud model theory is a new uncertainty modeling theory proposed by Chinese scientist Li et al. [21]. It is based on methods such as cognitive science, fuzzy mathematics, and probability statistics, aiming to deal with and describe uncertainty issues in the real world.

The cloud model transforms qualitative concepts into quantifiable cloud droplets, which can be represented by (Ex, En, He), where Ex, En, He represent the expectation, entropy, and hyper-entropy of the cloud droplets. Suppose U is the quantitative domain, and C is a qualitative concept of U. If a random number $\mu(x) \in [0,1]$ exists with a stable tendency for a random variable x in U. x is called a cloud droplet, where $\mu(x)$ is the membership degree of the cloud droplet.

2.2. Two-dimensional cloud model

The two-dimensional cloud model is a further development based on the one-dimensional cloud model. It utilizes six features to describe quantitative attributes, including feature numerical expectation (E_x, E_y), entropy (En_x, En_y), and hyper-entropy (He_x, He_y), to handle two influencing factors comprehensively. To obtain the numerical characteristics of a given two-dimensional normal cloud, cloud droplets are generated using a two-dimensional normal generator, and a mathematical model is established based on the given numerical characteristics.

$$\begin{cases} (x_i, y_i) = F(E_x, E_y, En_x, En_y) \\ (P_{xi}, P_{yi}) = F(En_x, En_y, He_x, He_y) \\ \mu_i = exp\left\{-\frac{1}{2}\left[\frac{(x_i-E_x)^2}{P_{xi}^2} + \frac{(y_i-E_y)^2}{P_{yi}^2}\right]\right\} \end{cases} \tag{1}$$

In equation (1), (x_i, y_i) represents the coordinates of the cloud droplet, F is a two-dimensional random function following the normal distribution, (P_{xi}, P_{yi}) denotes the conditional coordinates of the cloud droplet, and μ_i represents the membership degree. Therefore, the cloud model formed by cloud droplet $drop(x_i, y_i, \mu_i)$ is a two-dimensional normal cloud model [22].

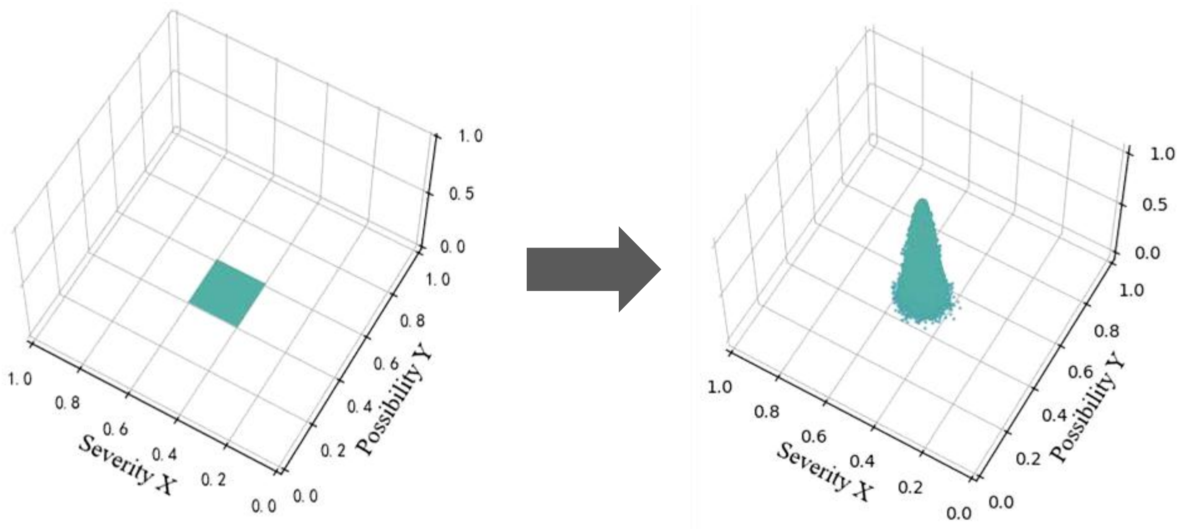

Figure 1. Improved risk matrix based on two-dimensional cloud model.

The two-dimensional cloud model can represent each region in the matrix chart as a comment cloud (see Figure 1). A risk matrix based on the two-dimensional cloud model can be obtained by transforming all regions into comment clouds. The following are the specific steps:

Step 1: Based on the actual situation of the research object, divide the possibility and severity into several assessment levels, each corresponding to an interval range $[Lmax_{min}]$.

Step 2: Based on the assessment level, select a numerical value from each interval range and use equation (2) to transform it into the numerical characteristics of the cloud model, reference [23], H_e is set to 0.01.

$$\begin{cases} \mathrm{E}_x = (L_{max} + L_{min})/2 \\ \mathrm{E}_n = (L_{max} - L_{min})/6 \\ H_e = 0.01 \end{cases} \tag{2}$$

Step 3: Manufacture cloud droplets and generate comment clouds based on the numerical characteristics obtained by equation (1).

Step 4: Repeat steps 2 and 3 to represent all regions in the matrix diagram as comment clouds.

3. BN based on fault tree

The fault tree is a systematic analytical method used to identify and analyze various potential causes and paths leading to accidents. It graphically represents the logical relationships among the bottom events, intermediate events, and top events that cause accidents.

Converting the fault tree into the BN [24]. BN is a statistical model that graphically represents probabilistic relationships between variables. It consists of a Directed Acyclic Graph (DAG) and a set of Conditional Probability Tables (CPT). Nodes in the DAG represent different events in the fault tree, while edges indicate the relationships between these events. Each node contains a CPT, describing the probability distribution of the node's value when the values of its parent nodes are known. CPT describes the "OR" logical gates in the fault tree through probability distributions [25].

Bayes's theorem is important in probability theory and is used to calculate conditional probability. The equation is as follows:

$$P(A|B) = \frac{P(A)P(B|A)}{P(B)} \tag{3}$$

Where: $P(A|B)$ is the probability of event A occurring given that event B has occurred, $P(B|A)$ is the probability of event B occurring given that event A has occurred, P(A) is the probability of event A occurring, and P(B) is the probability of event B occurring.

The posterior probability is the probability of the top event occurring, given that the bottom event has occurred. Based on the prior probabilities of the nodes, the posterior probability of the bottom event occurring can be obtained using the Bayes' theorem:

$$P\left(A = a_j | B = b\right) = \frac{P\left(A=a_j\right)B\left(B=b|A=a_j\right)}{P(B=b)} \tag{4}$$

Where: $P\left(A = a_j | B = b\right)$ is the posterior probability, representing the probability of event $A = a_j$ occurring given that event $B = b$ has occurred. $P\left(A = a_j\right)$ is the prior probability, and $B\left(B = b | A = a_j\right)$ is the conditional probability, representing the probability of event $B = b$ occurring given that event $A = a_j$ has occurred.

4. Highway engineering construction safety reliability risk assessment model based on two-dimensional cloud model-Bayesian network

4.1. Highway engineering construction safety reliability risk assessment process

Based on the two-dimensional cloud model and Bayesian network theory, a safety reliability risk assessment method of highway engineering construction is proposed. The process is illustrated in Figure 2. First, the Delphi method is employed to select risk factors and transform them into BN by constructing a fault tree. Then, based on the risk matrix method, multiple experts are invited to assess the bottom events, and the comprehensive cloud of bottom events is obtained through calculation. Finally, according to the assessment results, the probability of bottom events is calculated. The bi-inference function of BN is utilized to determine the probability of top events occurring and identify critical risk factors.

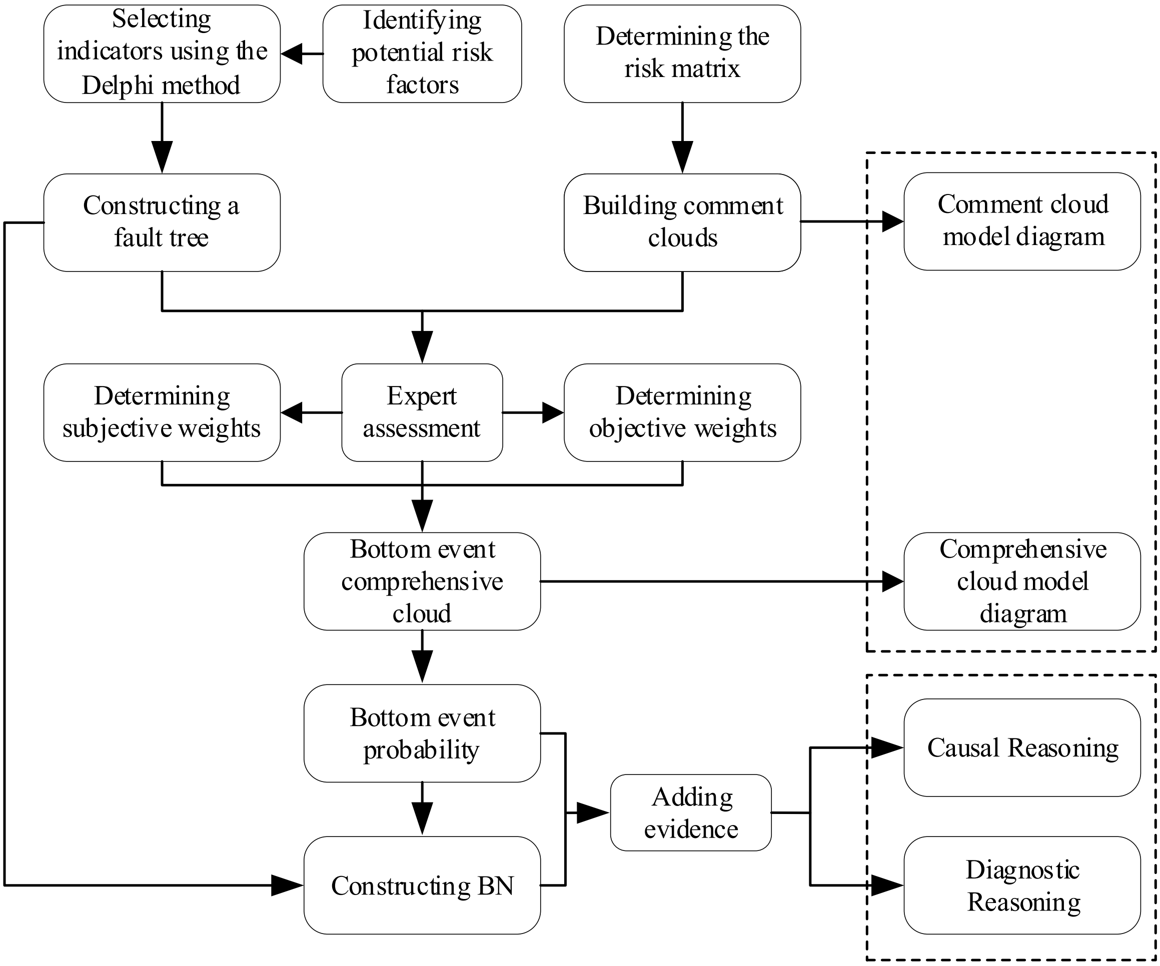

Figure 2. Highway engineering construction safety reliability risk assessment process.

4.2. Highway engineering construction safety reliability risk identification

Through extensive research and reference to relevant standards and specifications such as "Safety Technical Specifications for Highway Engineering Construction," considering the characteristics of highway engineering construction and incorporating expert opinions, potential risk factors have been categorized into accident risk, public health risk, social security risk, and natural disaster risk. Then, by utilizing the Delphi method [26] to screen risk events, the risk index system was ultimately determined to comprise four level I indexes and eighteen level II indexes, as shown in Table 1.

Table 1. Highway engineering construction safety reliability risk index system.

Level I index	Level II index
Accident risk X_1	Traffic accident X_{11}
	High-altitude falling accident X_{12}
	Mechanical equipment accident X_{13}
	Fire accident X_{14}
	Lifting and hoisting accident X_{15}
	Collapse accident X_{16}
	Electrocution accident X_{17}
Public health risk X_2	Acute infectious diseases X_{21}
	Food poisoning X_{22}
	Occupational hazards X_{23}
	Environmental pollution X_{24}
Social security risk X_3	Terrorist attack incident X_{31}
	Economic security incident X_{32}
	Mass incident X_{33}
	Cybersecurity incident X_{34}
Natural disaster risk X_4	Earthquake disaster X_{41}
	Flood disaster X_{42}
	Extreme weather X_{43}

Based on the above analysis, in highway engineering construction safety reliability risk is defined as the top event, with level I indexes as intermediate events and level II indexes as bottom events. The fault tree model represents the risk identification results, as shown in Figure 3.

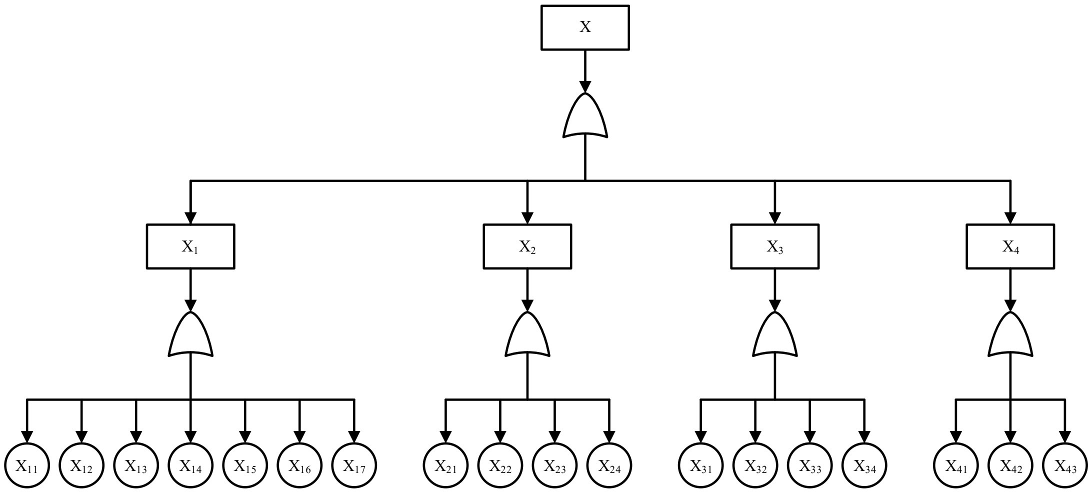

Figure 3. Highway engineering construction safety reliability risk fault tree model.

4.3. Expert weighting and risk assessment

4.3.1. Risk assessment matrix

The risk assessment levels are determined by combining expert recommendations, as shown in Table 2. The corresponding two-dimensional cloud risk matrix is plotted using equations (1) and (2), as depicted in Figure 4. It can be divided into four clusters from the bottom-left to the top-right, corresponding to low risk, medium risk, high risk, and extremely high risk. Then, experts provide the possibility and severity interval numbers for each bottom event occurrence based on the risk matrix assessment levels and the description table.

Table 2. Risk assessment levels and descriptions.

Level	Interval number	Possibility	Severity
I	[0,0.2)	Small	Slight casualties
II	[0.2,0.4)	Moderately small	Minor casualties, slight property damage

Level	Interval number	Possibility	Severity
III	[0.4,0.6)	Moderate	Moderate casualties, significant property damage
IV	[0.6,0.8)	Moderately large	Major casualties impacting construction
V	[0.8,1]	Large	Major casualties, causing a work stoppage

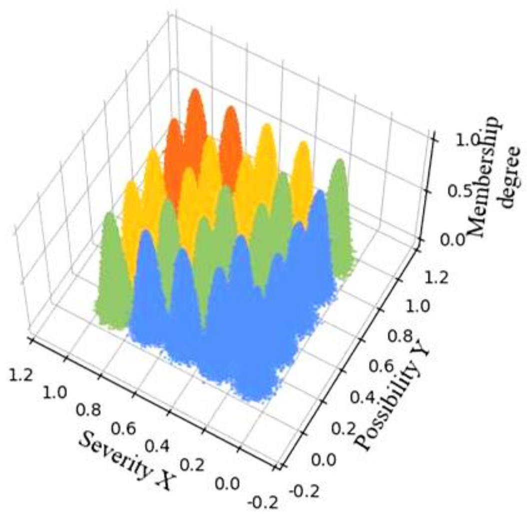

Figure 4. Two-dimensional cloud risk matrix.

4.3.2. Determination of expert weights

(1) Determination of subjective weights using the multi-index evaluation method

The method of multi-index evaluation is a comprehensive assessment approach used to evaluate various aspects of a system or plan. It weights and aggregates different indexes based on multiple evaluation criteria to derive an overall assessment result, aiding decision-making. Following reference [27], the multi-index evaluation method categorizes four elements: professional position, years of work experience, educational background, and age into several categories. Scores are computed for each category, and then the scores are normalized to obtain the subjective weight values m_k for each expert $k(k = 1,2,\cdots,D)$.

(2) Determination of objective weights using the entropy weight method

The entropy weight method is a multi-criteria decision-making approach used to determine the weights of various criteria. Based on the concept of information entropy, it evaluates the importance of criteria by calculating the entropy between them and then converts the entropy values into weights [28]. When the entropy value of expert k's assessment result is large, it is not conducive to identifying critical risk factors and should be assigned a smaller weight. Calculations are performed using equation (5).

$$N_k = \sum_{j=1}^{2}\left(-\frac{1}{\ln 18}\sum_{i=1}^{18}\varepsilon_{ij}^{k}\ln\varepsilon_{ij}^{k}\right) \tag{5}$$

$$n_k = \frac{a-N_k}{ak-\sum_{k=1}^{K}N_k} \tag{6}$$

Where: ε_{ij}^{k} represents the assessment result of expert k for bottom event i regarding assessment index j, $i \in (0,1,2,\cdots,18)$. a denotes the number of assessment indexes, and in this paper, the assessment indexes are possibility and severity. Thus, a=2.

(3) Comprehensive weight determination

Comprehensive weight involves the weighted summation of subjective and objective weights from various experts to obtain an integrated assessment result. It is computed using equation (7):

$$w_k = \alpha m_k + (1-\alpha)n_k \tag{7}$$

Where: $\alpha = 0.5$.

Substitute each expert's comprehensive weights and assessment results into equation (8) to obtain each bottom event's comprehensive cloud of assessment results. Then, use equation (1) to draw the corresponding two-dimensional cloud graph.

$$\begin{cases} E_x = \frac{\sum_{k=1}^{D}E_{xk}E_{nk}w_k}{\sum_{k=1}^{D}E_{nk}w_k} \\ E_n = \sum_{k=1}^{D}E_{nk}w_k \\ H_e = \frac{\sum_{k=1}^{D}H_{ek}E_{nk}w_k}{\sum_{k=1}^{D}E_{nk}w_k} \end{cases} \tag{8}$$

4.4. BN inference

After obtaining the assessment results for each bottom event, based on the comprehensive cloud of possibility for each bottom event, use the expectation curve as the membership curve and calculate the fuzzy possibility (FPS) using the left and right fuzzy sorting method [29].

$$y = exp\left\{-\frac{x-E_x}{2E_n^2}\right\} \tag{9}$$

$$FPS = \frac{[FPS_2+1-FPS_1]}{2} \tag{10}$$

The membership curve for FPS is obtained from equation (9), and the left and right FPS, namely FPS_1 and FPS_2, are calculated using equation (10). After substituting the FPS as the prior probability for the bottom event into the BN, a qualitative language is used to express the state of the BN nodes, with "Yes" indicating the occurrence of the event and "No" indicating the non-occurrence of the event. Based on the forward causal inference of the BN, the occurrence probability of highway engineering construction safety reliability risk is calculated. Using the reverse diagnostic inference of the BN, the known event occurrence states are integrated as evidence Z, and the conditional probabilities of the remaining events when the top event occurs are calculated using equation (4), i.e., the posterior probabilities. The larger the posterior probability of an event, the greater the possibility that it leads to the occurrence of the top event. This serves as the basis for identifying critical risk factors.

5. Cass study

5.1. Engineering background

The HB engineering has a total length of 67 km and a width of 69 km, with an actual construction mileage of 54.925 km, including 42 km of new construction and 12.925 km of reconstruction. The engineering includes 12 bridges, with one separated interchange crossing the Beijing-Guangzhou Railway. The geological conditions are favorable, with gentle terrain, and the construction of bridge piers and mainline bridges primarily employs friction piles and prefabricated structures. The expected duration of the project is 30 months.

The data relating to HB engineering is sourced from safety inspections during construction, self-inspection reports, production safety accident emergency plans, significant hazard source registers, and other relevant documents.

5.2. Determination of model parameters

Each was asked to rate the individual bottom events by inviting five experts from relevant fields. Subsequently, the ratings provided by each expert were normalized to obtain the subjective weight m_k for each expert k, as shown in Table 3.

Table 3. Information and subjective weights of each expert.

Expert	Title	Educational background	Years of work experience	Age	Score	Weight value
1	Project Manager	Ph.D.	≥ 20	≥ 50	38	0.268
2	Professor	Master's	15-19	40-49	30	0.211
3	Engineer	Master's	10-14	40-49	26	0.183
4	Associate Professor	Ph.D.	10-14	30-39	26	0.183
5	Engineer	Master's	6-9	30-39	22	0.155
Total					142	1

The subjective weights of the experts obtained from Table 3 are: $m = [m_1, m_2, m_3, m_4, m_5] = [0.268, 0.211, 0.183, 0.183, 0155]$.

Based on the relevant data from the construction process, the experts evaluated the possibility and severity of each bottom event of the engineering using the interval numbers in Table 2. Then, according to equations (5) and (6), the experts' objective weights were calculated as: $n = [n_1, n_2, n_3, n_4, n_5] = [0.222, 0.206, 0.190, 0.196, 0.186]$.

According to equation (7), the comprehensive weights of the experts were calculated as: $w = [w_1, w_2, w_3, w_4, w_5] = [0.245, 0.209, 0.186, 0.190, 0.170]$.

Taking the calculated comprehensive weights of the experts into equation (8), the comprehensive evaluation results clouds for each bottom event can be obtained. Then, according to equation (1), the corresponding two-dimensional clouds are plotted. The comprehensive cloud of accident risk assessment results is shown in Figure 5.

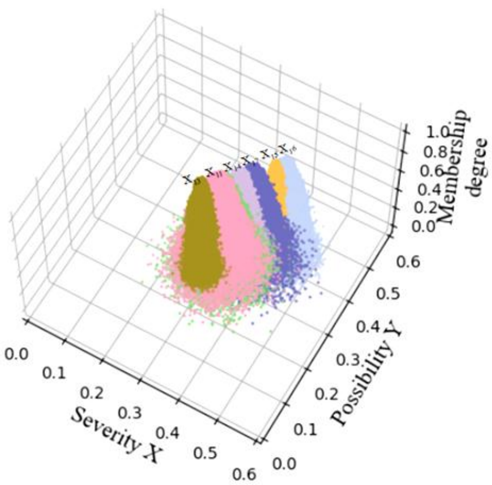

Figure 5. Comprehensive cloud of accident risk assessment results

5.3. Risk analysis

According to equations (9) and (10), the *FPS* values of each bottom event are calculated. After being incorporated into the BN, through causal inference, the occurrence probability of safety reliability risk in the HB engineering construction is determined to be 0.2933. Taking the probability *FPS* calculation of traffic accident X_{11} as an example, its calculation is illustrated in Figure 6. The BN parameters for safety reliability risk of the HB engineering construction are shown in Figure 7.

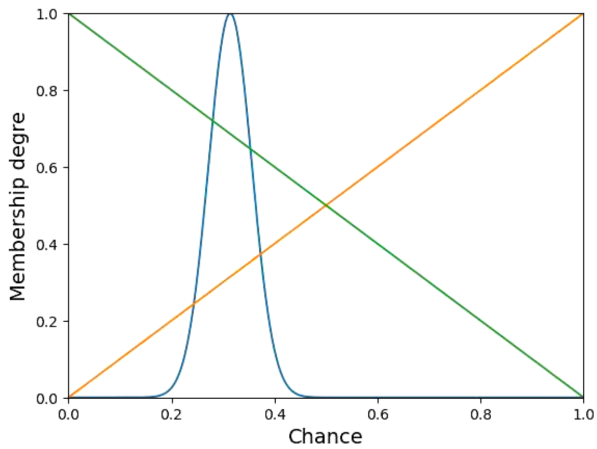

Figure 6. Calculation of the probability *FPS* of traffic accident X_{11}

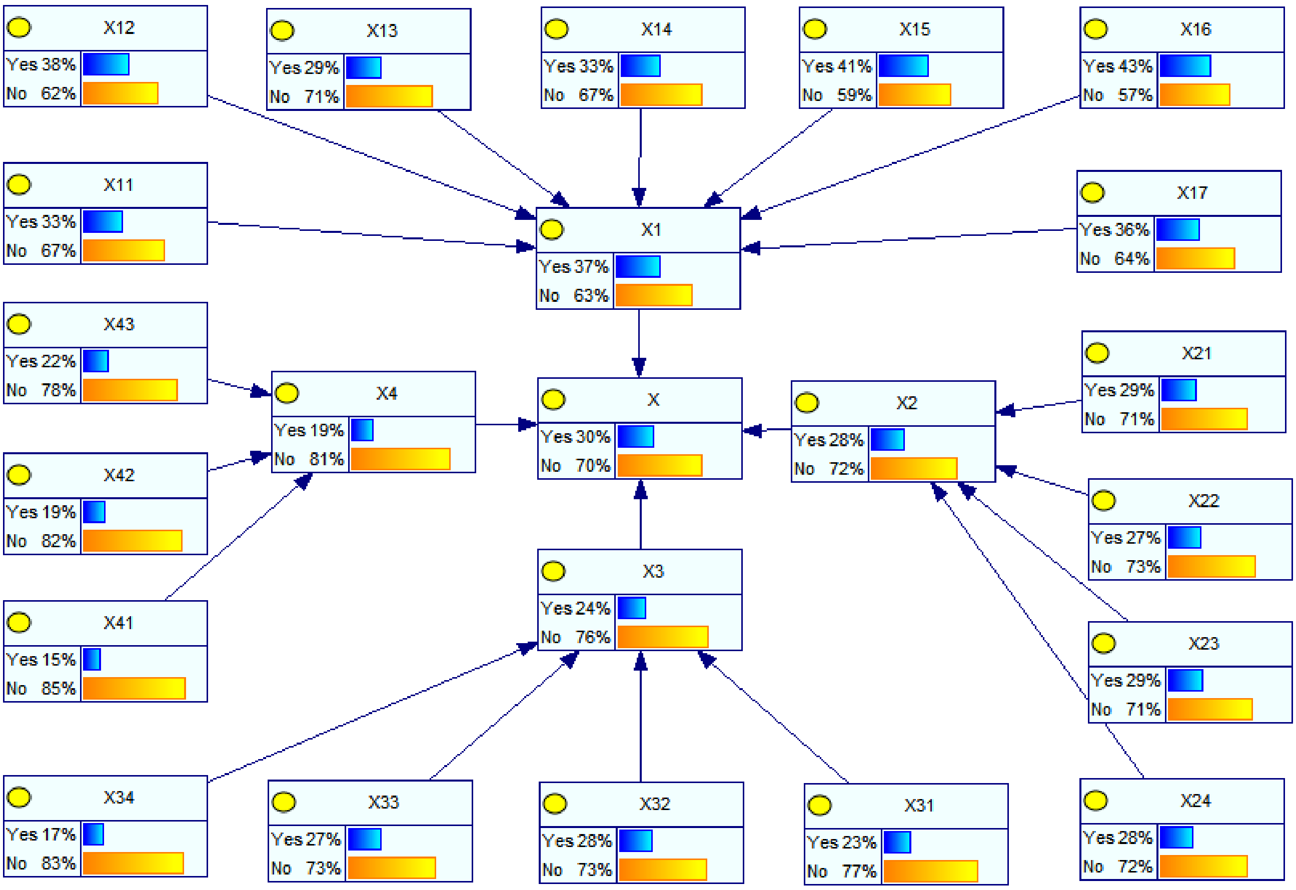

Figure 7. BN parameters for safety reliability risk of the HB engineering construction.

By setting the safety risk of the HB engineering construction *X* as the evidence node, assigning its state as "Yes", and utilizing the reverse inference of the BN model, the posterior probabilities of each bottom event can be obtained, thereby identifying the critical risk factors. The posterior probabilities of each bottom event are depicted in Figure 8. Hence, the critical risk factors are collapse accident X_{16}, lifting and hoisting accident X_{15}, high-altitude falling accident X_{12}, and electrocution accident X_{17}. Through comparison with Figures 4 and 5, it can be observed that all four factors are at a medium risk level.

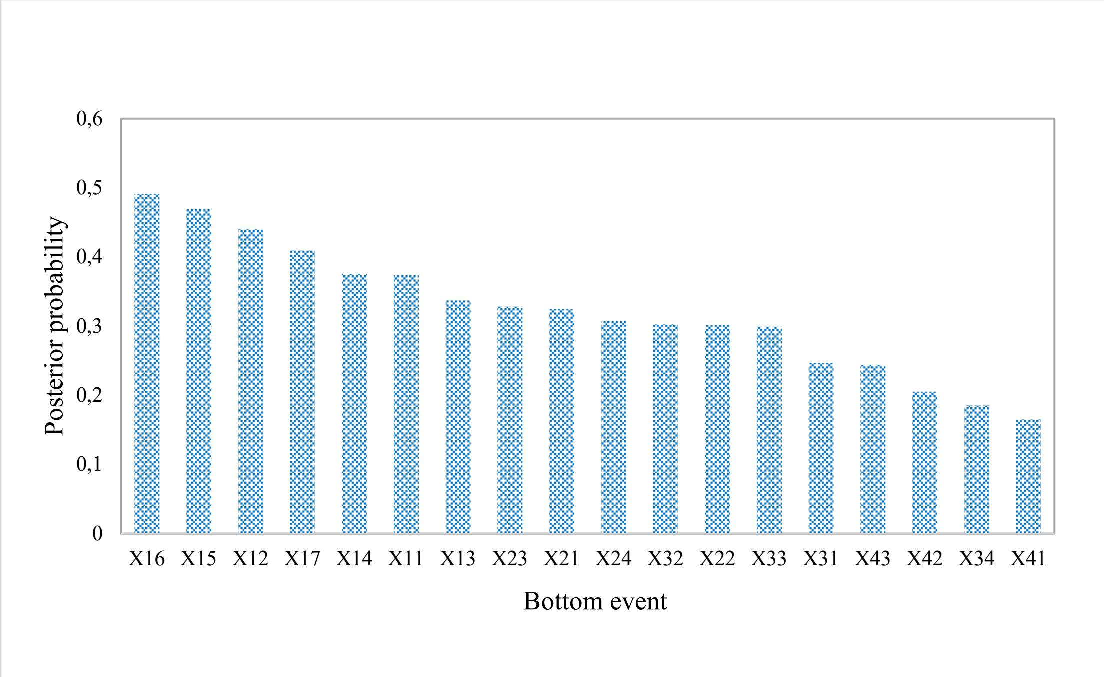

Figure 8. Posterior probabilities of bottom events.

Analyzing the causes of the four identified critical risk factors and proposing corresponding preventive measures as follows:

1) Collapses typically occur due to poorly constructed structures or infrastructure issues. Therefore, a thorough investigation and assessment of geological conditions and soil factors are necessary before construction. Additionally, setting up support structures and ensuring their secure anchorage.

2) Lifting and hoisting accident typically result from human error during operation or mechanical failures of lifting equipment and other reasons. Therefore, it is essential to have trained professionals handle the operation and ensure that construction personnel undergo the necessary training. Regular inspection and maintenance of lifting machinery should also be conducted to ensure their safe use.

3) High-altitude falling accident typically occur due to improper personnel operations, inadequate safety facilities, and other reasons. Therefore, high-quality safety equipment should be selected, and necessary safety training should be provided to construction personnel. Protective measures such as guardrails and safety nets should be installed at elevated areas and regularly maintained and replaced as needed.

4) Electrocution accident typically occur due to equipment damage, improper personnel operations, or adverse environmental conditions and other reasons. Therefore, electrical equipment should be inspected and maintained regularly to ensure proper operation. Necessary safety training should be provided to operators, and warning signs should be installed around electrical equipment.

5) From the perspective of managers, a more comprehensive risk prevention and control system can be constructed through system improvement, resource integration and strengthened supervision. For instance, in terms of system construction, managers should formulate strict construction safety management norms, clarify the responsibilities and operation standards of each link, and update the risk prevention and control plan regularly. In terms of resource coordination, funds should be rationally allocated for the purchase of advanced safety equipment and technological upgrades, and an expert team should be organized to conduct risk assessment and optimization of the construction plan. In terms of strengthening supervision, a multi-level safety inspection mechanism should be established, and information technology means should be used to monitor key processes in real-time. Safety performance should be linked to personnel assessment to enhance the safety responsibility awareness of all staff, reduce the probability of accidents from the source of management, and ensure the safety and reliability of highway engineering construction.

6. Conclusion

Regarding the issue of safety reliability risk assessment in highway engineering construction, an assessment system for highway engineering construction safety reliability risk has been developed, consisting of four Level I risk indexes, including accident risk, and eighteen Level II risk indexes, such as traffic accident. A risk assessment method based on the two-dimensional cloud model and BN is proposed to identify critical risk factors and perform causal inference for the safety of highway engineering construction. Taking the HB engineering as a case study, the probability of safety reliability risk occurrence in HB engineering construction is found to be 0.2933, while critical risk factors are identified, providing valuable reference for safety managers. From the assessment results, it is evident that collapse accident, lifting and hoisting accident, high-altitude falling accident, and electrocution accident are the top four critical risk factors, all at a medium risk level. Preventive measures are proposed for these critical risk factors, which can effectively reduce the probability of accidents and enhance the safety reliability of engineering construction. The case study results show that the model can accurately assess the safety reliability risk of highway engineering construction, providing a quantitative basis for project managers to develop scientific and reasonable risk management strategies, forming a complete closed loop of "risk identification - precise assessment - effective control - reliability improvement", and effectively ensuring the safety and stability of the entire cycle of highway engineering construction.

Future research can be further expanded in the following directions: Combining intelligent monitoring technology with the research methods of this study to construct a real-time dynamic risk assessment and early warning system to achieve active prevention and control of risks. Expand the research scope, apply the research results of this study to different types of transportation infrastructure construction projects, verify their universality, and continuously improve the evaluation system and methods to provide broader support for the safety and reliability management of the industry.

Reference

1. Panek A, Jacyna M, Jachimowski R, et al. Reliability and efficiency in technology selection in logistics facilities–multi-criteria decision support using the AHP method. Eksploatacja i Niezawodność, 2025, 27(2). https://doi.org/10.17531/ein/200684
2. Zhao Y, Zeng S, Guo J, et al. Mapping FRAM to BN through Accimap for system risk assessment: an application to heavy goods vehicle fire risk in road tunnels. Eksploatacja i Niezawodność–Maintenance and Reliability. 2025, 27(3). https://doi.org/10.17531/ein/200692
3. Che H, Zeng S, You Q, et al. A fault tree-based approach for aviation risk analysis considering mental workload overload. Eksploatacja i Niezawodność–Maintenance and Reliability. 2021, 23(4): 646-658. https://doi.org/10.17531/ein.2021.4.7
4. Zhang Z, Mao H, Liu Y, et al. A risk assessment method of aircraft structure damage maintenance interval considering fatigue crack growth and detection rate. Eksploatacja i Niezawodność – Maintenance and Reliability. 2023, 25(1). https://doi.org/10.17531/ein.2023.1.3
5. Wang YS. Research on quantitative prediction of highway project construction risk based on LSTM neural network. Highway, 2023, 68(12): 248-254.
6. Liu YL, Xi MY, Zhu FY, et al. Construction safety risk assessment model of high-speed railway bridge based on AHP+BP method. World Bridges, 2023, 51(03): 66-73.
7. Ji KK, Li ZZ, Liu S, et al. Safety risk assessment for port quay crane installation construction. China Safety Science Journal, 2022, 32(12): 102-109.
8. Wu JL. Development and application of construction safety risk assessing system to long-span steel box girder cable-stayed bridge. World Bridges, 2022, 50(03): 59-65.
9. Wu B, Zhu LP, Li YB, et al. Evaluation method and application of tunnel construction safety risk based on K-Means clustering model. Journal of Chongqing Jiaotong University (Natural Science), 2023, 42(11): 80-87.
10. Xu SL. Development of tunnel construction risk evaluation model and system under complex geology. Journal of Highway and Transportation Research and Development, 2023, 40(06): 174-181.
11. Shen JH, Liu SP. Application of fuzzy dynamic Bayesian network in risk evolution analysis of deep foundation pit construction. Journal of Safety and Environment: 1-12[2023-08-19].
12. Liu JH, Yu Y, Zhang ZX, et al. Risk assessment method of risers based on two-dimensional cloud model and BN. China Safety Science

Journal, 2022, 32(05): 147-154.
13. Zhou L. Dynamic evaluation of construction safety risk for approaching excavation of shield tunnel undercrossing high-speed railway based on Cloud Bayesian Network. Industrial Construction, 2023, 53(11): 226-233.
14. Zhang ZX, Wang B, Wang XF, et al. Safety-risk assessment for TBM construction of hydraulic tunnel based on fuzzy evidence reasoning. Processes, 2022, 10(12): https://doi.org/10.3390/pr10122597.
15. Tan BY, Zhu L, He BT. Research on safety risk assessment of long-span suspension bridge construction in deep valley in mountainous area based on cloud model. International Journal of Frontiers in Engineering Technology, 2022, 4(9): 55-60. https://doi.org/10.25236/IJFET.2022.040910
16. Lu Y, Gong PZ, Tang YC, et al. BIM-integrated construction safety risk assessment at the design stage of building projects. Automation in Construction, 2021, 124: 103553.
17. Zhang J, Wang YY, Zhou Q. Risk assessment of dam-break flood in Baoji section of the Qian river by using HEC-RAS modeling. Henan Science, 2024, 42(01): 147-156.
18. Yang YY, Zhao YL. Safety risk assessment of assembly building component hoisting based on combined weighted two-dimensional cloud model. Journal of Natural Disasters, 2022, 31(3): 167-174.
19. Zhang JM, Fan YY, Li ZQ. Seismic resilience evaluation of urban system based on two-dimensional cloud model. Engineering Journal of Wuhan University, 2024, 57(03): 311-321.
20. Wang L, Jin RB, Zhou JP, et al. Construction risk assessment of Yellow River Bridges based on combined empowerment method and two-dimensional cloud model. Applied Sciences, 2023, 13(19): 10942.
21. Li DY, Meng HJ, Shi XM. Affiliated cloud and affiliated cloud generator. Journal of Computer Research and Development, 1995, 32(6): 15-20.
22. Liu DW, Cao M, Tang Y, et al. Risk evaluation of water inrush in water-rich karst tunnel based on cloud model. Journal of Safety Science and Technology, 2021, 17(1): 7.
23. Chen L, Jin L, Huang B, et al. On the quantitative Bow-tie analysis of the tank leakage risk based on the 2-D cloud model. Journal of Safety and Environment, 2020, 20(03): 809-815.
24. Zhang H, Shen RC, Yuan GJ, et al. Risk evaluation on wellbore integrity of gas well based on Bayesian network. Journal of Safety Science and Technology, 2017, 13(9): 7.
25. Huang P, Lin XJ, Qin L, et al. Construction of experimental platform and teaching application of cable cabin fire in a utility tunnel. Research and Exploration in Laboratory, 2022(006): 041.
26. Xu ZL, Wang Z, Gao TY. Research on high-value patent screening based on AHP-Delphi Method—Taking rare earth permanent magnet industry as an example. Forum on Science and Technology in China, 2024(01): 62-71.
27. Lavasani SM, Ramzali N, Sabzalipour F, et al. Utilisation of Fuzzy Fault Tree Analysis (FFTA) for quantified risk analysis of leakage in abandoned oil and natural-gas wells. Ocean Engineering, 2015, 108: 729-737. https://doi.org/10.1016/j.oceaneng.2015.09.008
28. Qi HJ, He ZA, Huang T, et al. Research on safety risk assessment of slope excavation construction in Alpine and High Altitude Areas based on AHP-Entropy Weight Method. Highway, 2024, (01): 86-92[2024-01-25].
29. Li XHH, Chen GM, Jiang SY, et al, Developing a dynamic model for risk analysis under uncertainty: case of third-party damage on subsea pipelines. Journal of Loss Prevention in the Process Industries, 2018, 54: 289-302. https://doi.org/10.1016/j.jlp.2018.05.001