# Study On Identification of Construction Risk Pathways for Bridge Piers of Cross-Sea Bridges Based on FTA-BN Model

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**Abstract.** In order to explore the risks associated with the construction of bridge piers for cross-sea bridges, this paper presents a comprehensive analysis from five dimensions and proposes a model for identifying construction branch paths for cross-sea bridges based on Fault Tree Analysis (FTA) and Bayesian Network (BN). The model analyses, diagnoses, and evaluates system risks by using FTA structural inference and BN bidirectional inference. The research findings show that the probability of cross-sea bridge pier construction risk occurring is 36.8% from the perspective of the overall system's risk. From a sensitivity perspective, unexpected accidents and other risk situations are the most sensitive and are likely to cause top events to occur, with the probabilities of two nodes occurring being 36.0% and 37.5%, respectively. From a contribution perspective, poor construction conditions have the greatest impact, and when this node is in the most dangerous state, the probability of top events occurring is the highest at 81%. Poor construction conditions, physiological and physical degradation, and financial factors all have a risk occurrence probability exceeding 50%, and are significant risk factors leading to the occurrence of cross-sea bridge pier construction.

**Keywords:** Cross-Sea Bridges, Construction Risks, Fault Tree Analysis (FTA), and Bayesian Network (BN).

## 1. Introduction

Cross-sea bridges are considered one of the most optimal solutions for transportation across bays and straits, and they play a crucial role in connecting different regions and promoting socioeconomic development. As construction technology continues to advance, building these bridges has become increasingly complex. Despite efforts to minimize human error and improve mechanical equipment, materials, management, and environmental factors, construction accidents on cross-sea bridges remain frequent, resulting in numerous injuries, fatalities, and significant economic losses. These incidents also pose significant challenges for risk management and safety. Therefore, identifying risk pathways for cross-sea bridges has become a top priority for builders during the decades-long, or even century-long, construction process.

Currently, many studies have investigated the construction risks of bridges, especially sea-crossing bridges, from different perspectives, dimensions, and using various research methods. Hackl et al. [1] used unmanned aerial vehicles and modern photogrammetry techniques to obtain terrain information and applied it to bridge risk assessment. Qin et al. [2] used Interferometric Synthetic Aperture Radar (InSAR) technology based on satellite imagery to detect millimeter-level deformations, thereby monitoring the risk fluctuations of sea-crossing bridges. Guo et al. [3] evaluated the collision risk of ships passing through sea-crossing bridges under the influence of wind and water flow by analyzing the motion state of ships under wind and water flow coupling. Kim et al. [4] evaluated the accident frequency as a risk indicator by considering factors such as daily traffic volume, proportion of high-sided vehicles, and long-term distribution of wind speed and direction at the bridge site. LIN et al. [5] established a risk assessment model using fuzzy evaluation to evaluate the impact of marine environmental factors on each construction process, establish a risk event database, and conduct

comprehensive analysis of risk events. CHEN et al. [6] used the Work Breakdown Structure-Risk Breakdown Structure (WBS-RBS) and Analytic Hierarchy Process (AHP) to establish an evaluation model to improve the level of construction risk management for sea-crossing bridge projects. FANG et al. [7] combined fuzzy Analytic Hierarchy Process (FAHP) with Building Information Modeling (BIM) platform to develop a dynamic risk assessment system for sea-crossing bridge construction. This system provides risk warnings to engineering managers at each construction stage, and helps improve the efficiency of risk management. LIAO et al. [8] used various methods, such as engineering analogy, literature review, and expert investigation, to study and establish overall risk assessment indicators for complex marine construction safety. These indicators help identify and estimate the safety risks of complex marine construction, and enable the development of corresponding risk control measures.

Upon reviewing previous research, it is evident that most efforts have focused on developing risk identification techniques for cross-sea bridges. These studies have primarily relied on qualitative analysis methods to assess construction risks, with a focus on post-event analysis. However, the types of risks associated with cross-sea bridge construction are numerous and complex, and there is a lack of specific assessment models tailored to these risks, with insufficient analysis of their underlying causes.To address these gaps, this article takes a comprehensive approach from five dimensions, establishing a cross-sea bridge construction risk analysis model based on FTA-BN. By leveraging the strengths of fault tree analysis (FTA) in analyzing accident causes and Bayesian networks (BN) in studying complex causes and multiple variables with accurate probability calculation, the model provides a precise analysis and diagnosis of risk events.Through the use of FTA to clarify the risk factors and causal structure of cross-sea bridge construction risks and BN to consider the diversity and uncertainty of risk factors, bidirectional inference is conducted, and the model completes importance analysis, causal diagnosis, and risk assessment of cross-sea bridge construction risks. Following research on risk identification, this study proposes corresponding preventive measures to better prevent construction accidents associated with cross-sea bridges, improve the overall safety supervision mechanism, and increase the efficiency of risk control systems.

## 2. Identification of Construction Risks for Cross-Sea Bridge Piers

### 2.1. Human Factors

In the field of engineering construction, people play a crucial role as the primary participants. It is common for the physical and psychological factors of construction personnel to affect the progress of the project. Furthermore, the construction level and design proposals of the constructors significantly determine the quality of cross-sea bridge construction. Therefore, human factors comprise four critical aspects: physiological mechanism degradation ($Y_1$), inadequate safety awareness ($Y_2$), unqualified technical level of the construction team ($Y_3$), and defects in construction design proposals ($Y_4$). Understanding and addressing these factors is essential for ensuring the safe and successful completion of cross-sea bridge projects.

### 2.2. Mechanical equipment and material factors

The use of a significant amount of construction machinery and equipment is crucial to ensuring the smooth progress of construction projects. This is especially true for cross-sea bridge projects, which involve multiple offshore operations, high technical complexity, and a considerable amount of work. Various types of large-scale machinery and equipment are required to be used in conjunction with construction to overcome these challenges. Without construction machinery and equipment, the construction process would come to a halt.Furthermore, construction materials are a prerequisite for the successful completion of engineering projects. Poor quality materials may cause the entire safety construction system to collapse. Therefore, mechanical equipment and material factors are crucial, encompassing two essential aspects: unqualified construction materials ($Y_5$) and damaged construction equipment ($Y_6$).

### 2.3. Management Factors

The large scale of the cross-sea bridge project and the abundance of offshore operations have posed significant challenges to the project's construction and management. Implementing effective management methods is crucial for ensuring the progress of the construction project. Failure to properly manage the project, lack of coordination, and low work efficiency can lead to delays in project completion. Therefore, management factors that contribute to this include improper use of funds ($Y_7$), poor organization and management of the construction team ($Y_8$), and inadequate monitoring of the construction site ($Y_9$).

### 2.4. Environmental factors

The challenging natural environment in the construction area of a cross-sea bridge has a significant impact on the project's progress. If the relevant environmental conditions are not thoroughly predicted and understood before the construction begins, it can create substantial uncertainty and impede the project's normal construction progress. In the event of uncontrollable factors such as earthquakes and tsunamis, the project may face severe damage or catastrophic destruction. Therefore, environmental factors affecting the project include marine environmental risks ($Y_{10}$), geological environmental risks ($Y_{11}$), meteorological risks ($Y_{12}$), and poor construction conditions ($Y_{13}$). It is crucial to address these environmental factors to ensure the successful completion of the project.

### 2.5. Types of accidents

The construction of a cross-sea bridge presents various challenges, including a long construction period, high technical complexity, and significant risks associated with offshore operations. These challenges have led to the frequent occurrence of various types of accidents. Poor risk prediction by workers, failure to consider the complexity and difficulty of offshore construction, and other factors can result in serious quality and safety accidents during construction, leading to project timeline delays. As a result, accidents can be categorized into four types: natural disasters ($M_1$), quality accidents ($M_2$), unexpected accidents ($M_3$), and other risk events ($M_4$). It is critical to address these accident types to ensure the successful completion of the project.

Based on the literature review and analysis of accident data, this article presents the risk identification results for the construction of the cross-sea bridge, as shown in Table 1.

**Table. 1** Factors affecting construction risks of cross-sea bridges

| Sources of Risk | Major Risk Factors | Code | Indicator Description | References |
|---|---|---|---|---|
| Human Factors | Degradation of Physiological and Physical Mechanisms | $Y_1$ | Physical or Age-related Inadequacy for Construction in Aquatic Environments. | [6] |
| | Inadequate Psychological Safety Awareness | $Y_2$ | Showing off, Working under the Influence of Alcohol, and Disregarding Safety. | [6] |
| | Unqualified Technical Skills of Construction Teams | $Y_3$ | Insufficient Training of Construction Teams, Leading to Low Overall Quality. | [6] |
| | Defects in Construction Design Plans | $Y_4$ | Lack of Relevant Code Knowledge among Designers, Resulting in Unreasonable Construction Design Plans. | [6] |
| Factors Related to Mechanical Equipment and Materials | Use of Unqualified Construction Materials | $Y_5$ | The use of unqualified construction materials can impact the quality and service life of the project. | [9] |

| | | | | |
|---|---|---|---|---|
| | Damage to Construction Equipment | $Y_6$ | The use of unqualified or malfunctioning mechanical equipment can lead to frequent accidents. | [9] |
| Management Factors | Improper Use of Funds | $Y_7$ | Improper use of funds can cause project delays and postponements. | [6] |
| | Low Organizational and Management Level of Construction Teams | $Y_8$ | Insufficient Training of Management Personnel, some of whom are Irresponsible and Unaccountable. | [6] |
| | Lack of Strict Monitoring at the Construction Site | $Y_9$ | Inadequate supervision and control of all personnel, materials, and equipment at the construction site, combined with irresponsible site management personnel, can lead to material loss. | [6] |
| Environmental Factors | Marine Environmental Risks | $Y_{10}$ | Various ocean currents, waves, tsunamis, and other phenomena caused by the ocean. | [8] |
| | Geological Environmental Risks | $Y_{11}$ | Geological instability, insufficient soil resistance in the foundation. | [8] |
| | Meteorological Risk | $Y_{12}$ | The impact of weather conditions such as typhoons and heavy snow on construction progress and personnel. | [8] |
| | Poor construction conditions at the foundation level | $Y_{13}$ | The construction protection measures are inadequate, and there are few construction signs. | [5] |
| Types of accidents | Natural disasters | $M_1$ | The impact of severe weather and geological disasters on construction. | [5] |
| | Quality accidents | $M_2$ | Construction quality accidents refer to structural and quality defects in the construction process caused by construction factors. | [9] |
| | Unexpected accidents | $M_3$ | Accidents such as project delays and personnel injuries caused by improper operations and management. | [9] |
| | Other risk events | $M_4$ | Risk situations that do not fall under the above categories, such as environmental pollution accidents. | [9] |

## 3. Fault tree analysis

FTA is a graphical modeling technique used to investigate system failures at all levels and the root causes of failures [10]. FTA can scientifically and intuitively show the cause structure of the top event and clarify the context of the top event. Through analysis and deduction, this method takes the system target fault ( top event ) that needs to be analyzed as the starting point, gradually analyzes the causes of various events, and finally finds the basic inducement ( basic event ) that leads to the event. Based on this idea, FTA is represented as a directed acyclic network with an inverted tree structure consisting of certain logical symbols to show the various ways in which a particular fault or failure may occur [11]. The events can be divided into the top event, intermediate event, and bottom event. The events are connected by logic gates and analyzed systematically.

The FTA schematic diagram is shown in Figure 1, where the ' T ' event is the top event, events ' A ' and ' B ' are intermediate events, and ' X1-X4 ' is the bottom event.

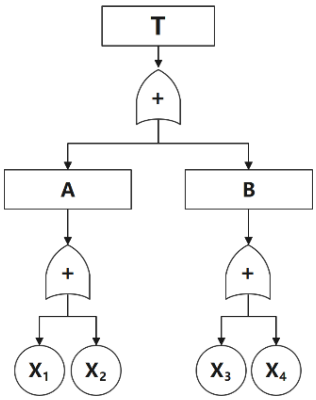



**Figure. 1** FTA Demonstration

## 4. Bayesian network

Bayesian network is a reasoning model based on probability theory and graph theory, which is widely used in risk and security analysis under uncertain and probabilistic knowledge [12]. Bayesian network is suitable for complex uncertainty problems. It can study multi-modal factors and use a conditional probability table to quantify the relationship between factors. The probability of top event failure is calculated by forward reasoning to clarify the security of the system. The influence degree of a single factor on the system is studied by reverse diagnosis, and the critical control points are defined. Based on the Bayesian formula, the model uses the prior probability to reflect the estimation of the model parameters and then combines the data to obtain the posterior probability distribution of the model parameters, to realize the comprehensive utilization of empirical information and sample data information to improve the accuracy of the results.

Bayesian rule is a statistical principle based on probability theory, which combines prior knowledge with evidence. It can perform probabilistic reasoning in both positive and negative directions in an uncertain environment.

The prior probability and posterior probability are relative to the fact that whether an undetermined fact has occurred or not. Let X and Y be two random variables, Y = y be a hypothesis, and X = x be a set of evidence. If the evidence determines whether the fact has occurred or not, it is the prior probability of random variable Y; the corresponding probability is the posterior probability of Y.

Bayesian theorem describes the relationship between prior probability and posterior probability as shown in Equation (1):

$$P(Y = y|X = x) = \frac{P(Y=y)P(X = x|Y = y)}{P(X=x)} \quad (1)$$

# 5. Calculation and analysis

## 5.1. FTA Construction

In the fault tree of the cause of the process rework, a total of 17 bottom events and 5 intermediate events were selected. Combined with expert experience and related accident cases, the top event number was set to T. The intermediate event is mainly divided into two layers, from top to bottom with M, A number, the bottom event begins with Y and is numbered in turn. The FTA diagram of the risk factors of the construction of the bridge column of the sea-crossing bridge is shown in figure 2.

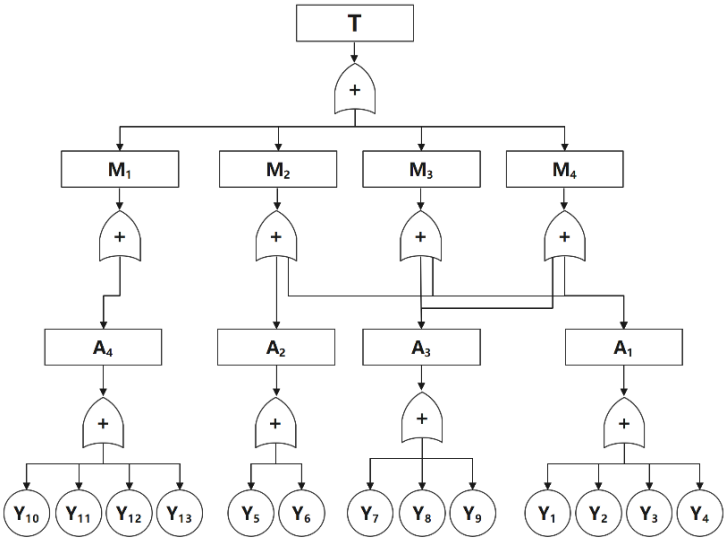



**Figure. 2** FTA model for construction risk of bridge pillars of cross-sea bridge

## 5.2. BN Construction

Following the mapping rules, the fault tree of the construction risk of the cross-sea bridge column shown in Figure 2 is transformed to obtain the Bayesian network shown in Figure 3.

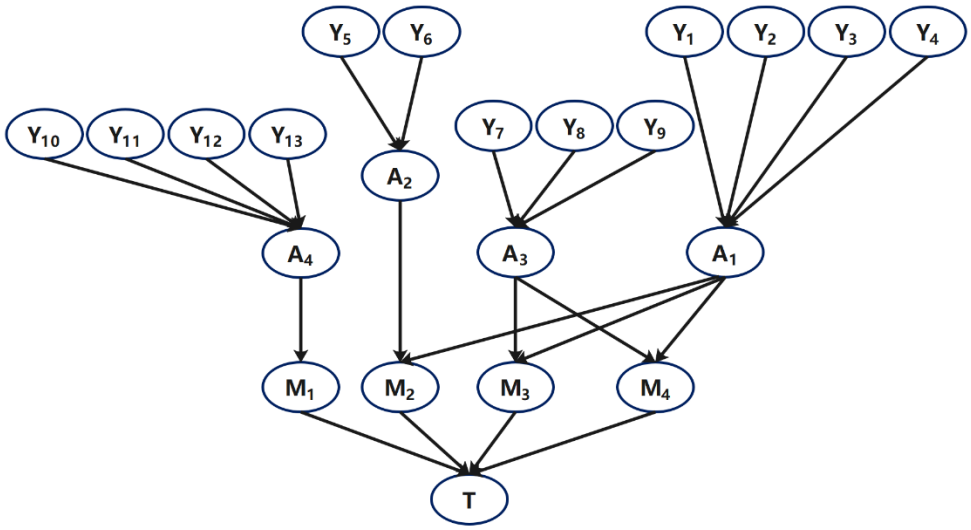



**Figure. 3** BN model for construction risk of bridge pllers of cross sea bridge

### 5.3. Analysis of BN

#### 5.3.1 Acquisition of Prior Probability

In Bayesian network, the prior probability is the marginal distribution of its variables, which is often obtained from past experience and analysis, and can be obtained by calculating the frequency of a large number of statistical historical data or scoring according to expert experience. Due to the lack of relevant data, this paper combines the statistics and research of bridge column construction accidents of cross-sea bridge, refers to the evaluation of experts in related fields, and converts the incident frequency into probability value through probability revision. According to the principle of mapping fault tree to Bayesian network, the prior probability of related risk factors is obtained. See Table 2 for the prior probability of risk factors in the construction of bridge columns of cross-sea bridges.

**Table. 2** Prior probability of basic events in Bayesian networks

| Event number | P(T=Y)=1 | P(T=N)=1 | Event number | P(T=Y)=1 | P(T=N)=1 |
|---|---|---|---|---|---|
| $Y_1$ | 0.65 | 0.35 | $Y_8$ | 0.31 | 0.69 |
| $Y_2$ | 0.14 | 0.86 | $Y_9$ | 0.22 | 0.78 |
| $Y_3$ | 0.11 | 0.89 | $Y_{10}$ | 0.1 | 0.9 |
| $Y_4$ | 0.18 | 0.82 | $Y_{11}$ | 0.05 | 0.95 |
| $Y_5$ | 0.22 | 0.78 | $Y_{12}$ | 0.25 | 0.75 |
| $Y_6$ | 0.11 | 0.89 | $Y_{13}$ | 0.81 | 0.19 |
| $Y_7$ | 0.42 | 0.58 | - | - | - |

According to the logic gate rules of fault tree, the conditional probability table of all non-root nodes of Bayesian network can be obtained, which is not listed in this paper because of the large amount of data. The conditional probability of the dependency relationship between the intermediate node A3 and its child nodes Y7, Y8 and Y9 is shown in Table 3. A3, Y7, Y8, Y9 and other nodes indicate Y when they occur, and N when they do not occur.

**Table. 3** Conditional Probability Table of A3 Node of Bayesian Network

| $Y_7$ | | Y | | | | N | | | |
|---|---|---|---|---|---|---|---|---|---|
| $Y_8$ | | Y | | N | | Y | | N | |
| $Y_9$ | | Y | N | Y | N | Y | N | Y | N |
| $A_3$ | P(Y) | 0.9 | 0.87 | 0.71 | 0.48 | 0.8 | 0.34 | 0.28 | 0.05 |
| | P(N) | 0.1 | 0.13 | 0.29 | 0.52 | 0.2 | 0.66 | 0.72 | 0.95 |

#### 5.3.2 BN Forward Reasoning

Forward reasoning based on the FTA-BN model can predict the probability of the construction risk of the bridge column of the sea-crossing bridge. In Bayesian network model, the prior probability of root node and the conditional probability of non-root node are set in advance, and the probability will be transferred from root node to leaf node, thus the probability of leaf node can be obtained. Based on BN formula, combined with Genle software, the result of forward reasoning is shown in Figure 4, and it can be concluded that the probability of bridge column construction risk of cross-sea bridge is P(T=Y)=36.8%.

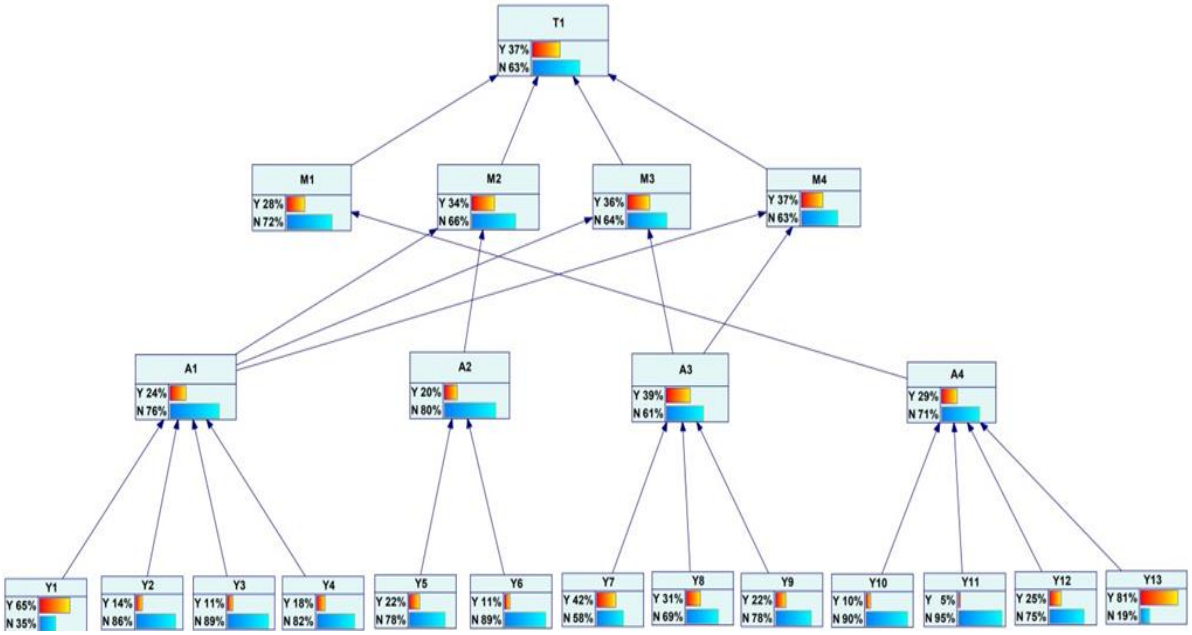



**Figure. 4** BN forward reasoning

By setting the conditional probability of each intermediate node in Genle software, the probability of occurrence of each risk factor can be obtained, and it can be concluded that the probability of occurrence of A3 (management factor) and A4 (environmental factor) is high, and it is necessary to conduct investigation in advance. However, the risk accident of the bridge column of the cross-sea bridge is the result of the interaction of various factors, and the probability of each accident can also be obtained by BN forward reasoning. Finally, it is concluded that the probability of M3 (accident) and M4 (other risk events) is very high, which is 36.0% and 37.5% respectively, which is in line with the engineering situation and shows that the BN network constructed is reasonable.

### 5.3.3 BN Reverse Reasoning

When the bridge column accident of the cross-sea bridge occurs, the posterior probability of each risk factor can be obtained by setting the state of the leaf node in Bayesian network as "Occurred", that is, P(T=Y)=1, and using Genle software for reverse reasoning. At this time, the reverse result is shown in Figure 5:

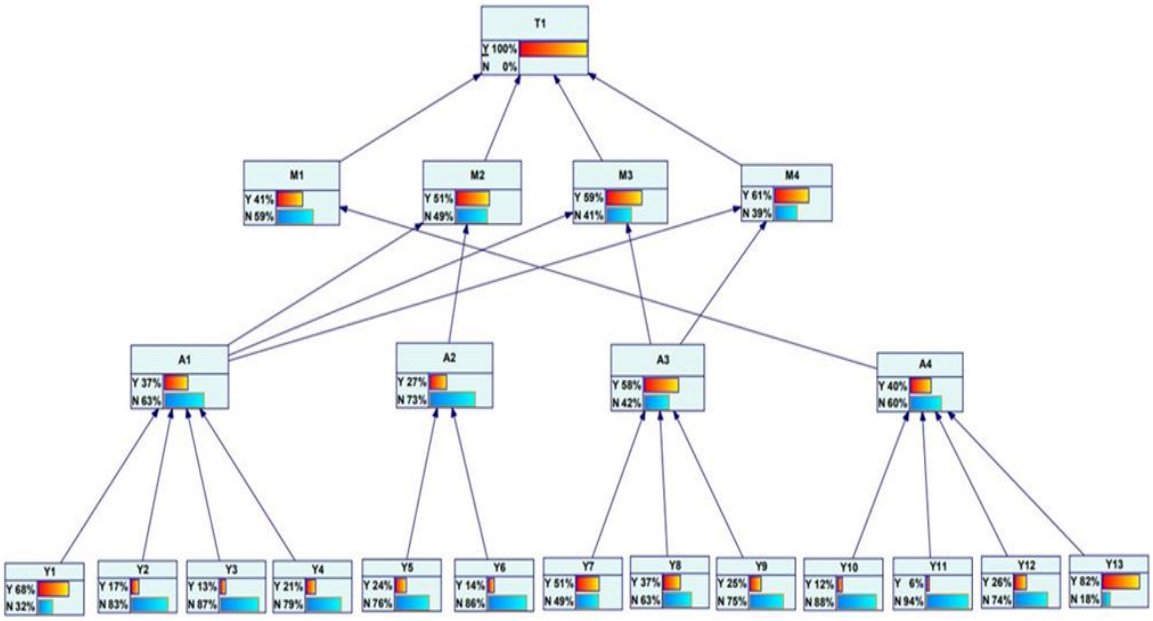



**Figure. 5** BN Reverse Inference Diagnosis

By analyzing the posterior probability of the construction risk of the bridge column of the cross-sea bridge, when the top event must occur, the posterior probability of the basic event has changed greatly compared with the prior probability. The probability of M4 (other risk events) is over 60%, and the probability of M3 (accidents) and M2 (quality accidents) is over 50%. According to the posterior probability in Figure 5, the posterior probability (P(Y13=Y)=82%) of Y13 (poor foundation construction conditions) is the largest, and the ranking of importance is the highest, which is the main factor leading to the construction risk of the bridge column of the sea-crossing bridge. Therefore, the risk factor should be investigated first, and after this factor is controlled, other factors should be investigated one by one. Through BN reverse reasoning, it can be concluded that Y13 (poor foundation construction conditions), Y1 (physiological and physical deterioration) and Y7 (financial factors) are the most dangerous factors that lead to the construction of bridge columns across the sea [12]. Therefore, in the process of construction, corresponding measures should be taken in time to avoid causing greater losses.

### 5.3.4 BN sensitivity analysis

In the BN model, the difference is obtained through posterior probability-prior probability, and the importance of each index is obtained. The tornado chart is used to display the risk sensitivity and influence degree of each sensitivity influencing factor, and the risk is quantitatively analyzed intuitively and conspicuously, so as to conduct sensitivity analysis, and the calculated BN sensitivity result is shown in Figure 6.

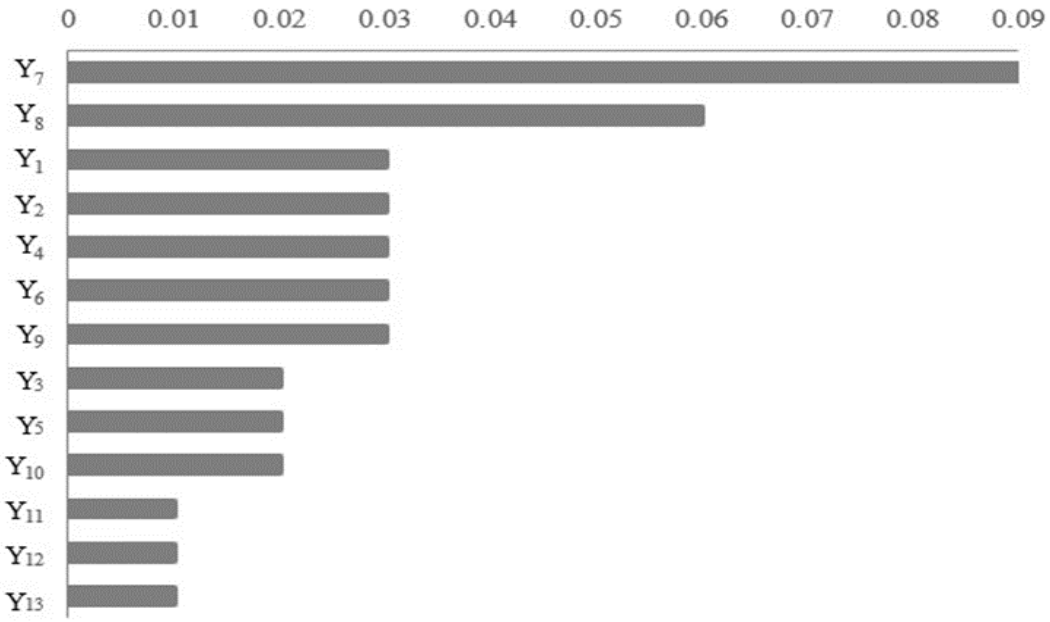



**Figure. 6** Sensitivity Analysis

As can be seen from Figure 6, all the influencing factors are positive correlation factors, among which Y7 (financial factor) is the most affected, followed by Y8 (low level of organization and management of construction team). According to the above analysis, it is necessary to focus on these factors in the process of risk investigation to maximize work efficiency. Among them, Y11 (geological environment risk), Y12(meteorological condition risk) and Y13 (poor foundation construction conditions) are the least affected, so in the process of investigation, personnel deployment can be reduced and cost control can be strengthened.

## 6. Conclusions

In this paper, FTA-BN model is introduced into the field of risk assessment of bridge column construction of cross-sea bridge, and the difficulty of modeling Bayesian network BN is reduced by

using fault tree FAT, and the FTA-BN model of bridge column construction risk of cross-sea bridge is established, and the conclusions are as follows:

(1) The probability of the bridge column construction risk is 36.8%, and the overall risk level of the project is low. Among all kinds of accidents, accidents and other risky events have a high probability and need special attention. When the bridge column accident of the sea-crossing bridge has occurred, poor foundation construction conditions, deterioration of physiological and physical functions and financial factors are the most likely risk factors leading to the bridge column construction of the sea-crossing bridge. Therefore, in the construction process, these factors can be taken as the key investigation factors, and preventive measures should be taken in advance.

(2) The results of sensitivity analysis show that the risk level of bridge column construction is the most sensitive to the change of capital factors, followed by factors such as the organization and management level of the construction team, so the capital plan should be made in advance to ensure the normal progress of construction; According to the tornado chart, management and personnel factors have a strong influence on the risk of bridge column construction, which is the focus of risk management and control. Factors that cannot be controlled by human beings, such as environmental factors, can reduce personnel deployment and reduce costs. This study can consider introducing complex network, system engineering theory and other methods to deeply explore the complex relationship between factors.

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