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# Risk assessment of wind resistance safety of cable-stayed bridge based on Bayesian network

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**Abstract.** Wind-induced risk accidents of cable-stayed Bridges exist all the time. It is important to evaluate the wind-resistant risk of cable-stayed Bridges. In order to better reduce and avoid risks in cable-stayed bridge engineering, this paper collates and analyzes previous studies, combines Bayesian network model with practical engineering problems, and establishes a risk assessment model for wind resistance risk assessment of cable-stayed bridge. Taking Humen Bridge in Guangdong Province of China as an example, the paper carrying out relevant derivation and discussion.

**Keywords:** cable-stayed bridge, risk assessment, wind resistance, bayesian network.

## 1. Introduction

The cable-stayed bridge comes from the cable bridge, which has a similar structure system with modern cable-stayed bridge in China, Southeast Asia, Indonesia and other areas. Before the middle of the 20th century, the development of research and application of cable-stayed bridge was very slow due to the limitation of steel quality and performance, the lack of mechanical analysis knowledge of cable-stayed bridge and a series of material and technical problems.

After World War II, with the rapid development of economy and science, the invention of high-strength steel, the emergence of more advanced and rational structural analysis techniques and so on, vigorously promote the development of large-scale bridge engineering construction speed and scale. Cable-stayed bridge has become one of the most competitive bridge types in modern times due to its superior crossing ability and unique beautiful appearance.

But with the increase of span of cable-stayed bridge, its structural stiffness decreases rapidly, its flexibility becomes more obvious, and it becomes more sensitive to wind load [1], so the problem of wind-induced vibration of the bridge is more prominent. Under the action of wind load, the stability and safety of cable-stayed bridges cannot be ignored. For example, in China, the vibration of Humen Bridge has aroused public concern. And last century, the Tacoma Bridge in Washington State on the west coast of the United States collapsed due to wind load. There have also been bridge accidents in India and Croatia. Based on these accident cases, the safety of wind-induced vibration of bridge caused by wind load must be paid enough attention.

From 2000 to the present, driven by the Malta Conference and several major international conferences and major construction engineering, as well as the increasing attention of the society and the government to the risk of bridge engineering, the research on bridge risk assessment has received great attention and developed rapidly. Since the theoretical research on bridge risk assessment is still at the primary level, compared with risk research in other industries, there is still more room for improvement.

In 2003, Wu Qihe of Southwest Jiaotong University proposed to evaluate the structural safety of reinforced concrete bridges based on reliability theory in his master's thesis and proposed a reliability assessment model for reinforced concrete girder bridges [2].

In 2004, Liu Zhiwen conducted a study on the wind risk assessment of cable-stayed bridges and established a risk evaluation system for cable-stayed bridges [3].

Dr. Xin Ruan from Tongji University gave a basic definition of bridge risk in his doctoral dissertation in 2006, constructed a system for bridge risk assessment research, counted and analyzed collected bridge risk accidents, studied key issues in bridge risk assessment, and established a basic theoretical framework for bridge risk assessment system [4].

In 2007, Zhang Jie conducted a study related to the risk analysis method for large-span bridges in the construction phase, which improved the traditional hierarchical analysis method, proposed a fuzzy hierarchical analysis method and identified the risk sources for large-span bridges in the construction phase, and introduced artificial intelligence techniques in the estimation of risk probability to establish a numerical model for the failure loss of large-span bridges in the construction phase [5].

In 2009, Song Junho and Kang Wonhee proposed a probabilistic risk assessment method based on reliability, and introduced the application of Bayesian networks in system safety, reliability and risk assessment. Compared with other classical methods such as impact analysis and event tree analysis, the accuracy and effectiveness of these two methods are analyzed, as well as their relative advantages in different practical application scenarios [6].

P. Gehl et al. proposed a Bayesian network model based on the system reliability matrix for bridge risk assessment in 2017. Based on the analysis of various accidents of American simply supported Bridges, the risk loss levels corresponding to different failure modes of all components are defined to carry out the bridge risk assessment [7].

Yang Dong conducted a study on the structural safety risk assessment of in-service bridges in 2018, considering various factors affecting the structural safety of bridges. The risk assessment of structural safety of bridges in use was carried out by Yang, considering various factors affecting the structural safety of bridges, and using cloud modeling methods [8].

In 2019, based on the existing research results of bridge operation risk, Yang Shuzhi conducted a study on the risk assessment of bridge operation period [9].

At present, more and more attention has been paid to the research on the risk assessment of Bridges. However, the quantitative risk assessment of cable-stayed Bridges using Bayesian networks is still rare, and more analysis is still done on simple bridge structures and preliminary evaluation analysis. Therefore, it is practical and innovative to construct a quantitative performance-based wind risk assessment model for cable-stayed Bridges by using Bayesian networks.

## 2. Methodology

### *2.1. Bayesian network*

*2.1.1. Basic principles of Bayesian network.* Bayesian theory is a statistical method that differs from traditional probability. It treats unknowns as random variables and combines a priori information for analysis and derivation [10]. Bayesian network is a graphical probabilistic model based on probabilistic reasoning. As an uncertain causal association model, it has a strong ability to deal with uncertain problems. The density function form of the Bayesian formula is as follows:

$$\mathrm{pdf}(\theta|y) = \frac{\mathrm{pdf}(\theta)\times\mathrm{pdf}(y|\theta)}{\mathrm{pdf}(y)} [11] \tag{1}$$

Where, θ is the parameter to be estimated; y is the overall index; pdf (θ) is the prior probability of the parameter; pdf (y/θ) represents the likelihood degree of the overall index under the condition that the parameter is θ. pdf (θ/y) represents the probability of the parameter θ under y condition which is the posterior distribution density. The parameter value corresponding to the maximum value is the target value we are looking for. This parameter value represents the minimum gap between the theoretical value of the finite element model and the field measured data.

*2.1.2. Inference methods of Bayesian network.* In Bayesian networks, accurate probability distributions (marginal and conditional) of target variables can be deduced after assigning values to a specific set of evidence variables. In large-scale networks, the computational complexity increases exponentially with the increase of the amount of data, and precise reasoning cannot be fully implemented. Approximate reasoning algorithm can also be used to obtain approximate solutions with lower complexity and higher computational efficiency.

*2.1.3. Basic steps for wind resistance risk assessment of cable-stayed bridges.* Using Bayesian networks to analyze the wind risk of Bridges can be distilled into the following four main steps:Set up the main event and sub-event of risk assessment, construct the sub-event network of each level through logical relationship, and map back to the main event to form the fault tree of wind resistance accident of cable-stayed bridge.

Determine risk specification strength criteria. According to the probability of accident risk and the intensity of loss caused by accident risk, a set of criteria is established to measure the wind risk strength of cable-stayed bridge.

Combine fault trees in (1) and criteria in (2) to form a Bayesian network for bridge wind resistance risk.

Quantify the wind risk of cable-stayed bridge and determine the model parameters of Bayesian network.

**Figure 1.** Wind resistance risk analysis of cable-stayed bridge flow chart based on Bayesian network.

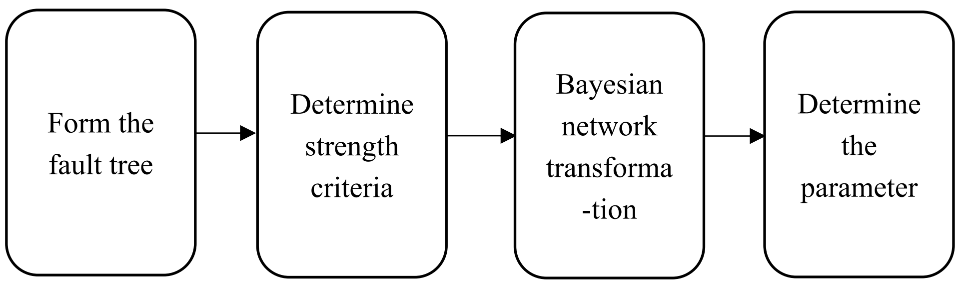


**Figure 1.**

*2.2. Bayesian network modeling*

*2.2.1. Determine the wind risk source of cable-stayed bridge.* For the cable-stayed bridge structure, once static wind instability, flutter and other phenomena occur, the bridge structure will be destroyed. Although the vortex-induced vibration has no obvious destructive effect on the bridge structure, it still has adverse effects on the bridge structure or components. Based on the existing research results of bridge wind resistance, the identification and analysis of the factors affecting the static wind instability, flutter and vortex-induced vibration of the bridge will be carried out in the following parts.

Static wind instability

Static wind instability has the characteristics of sudden strong, destructive. Through investigation and analysis of existing research results on static wind stability of Bridges, the influencing factors of static wind instability of cable-stayed Bridges can be classified into the following three categories [12]:

a) Static wind instability caused by different three component force coefficients of main girder of cable-stayed bridge.

b) Static wind instability caused by fractured cable of cable-stayed bridge.

c) Static wind instability caused by excessive initial wind attack angle.

According to the above analysis results, the fault tree can be drawn to determine the main influencing factors of the static wind instability.

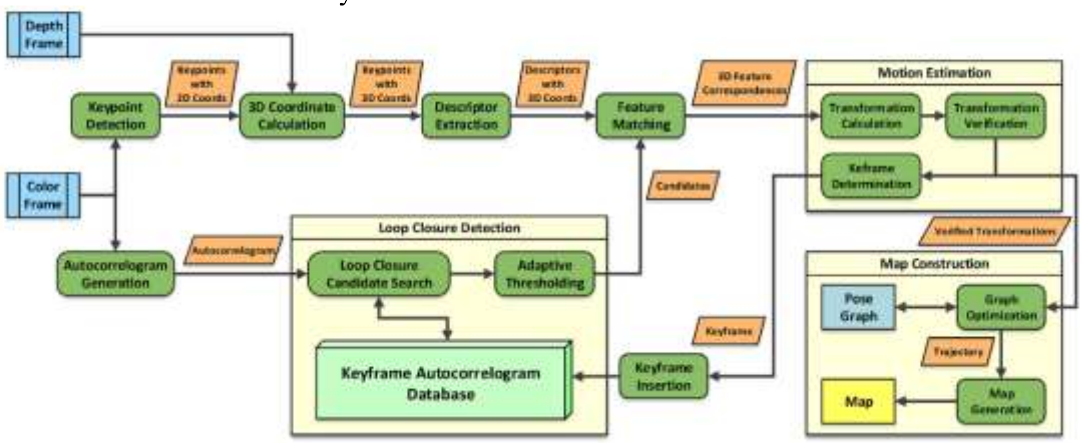


**Figure 3.** Whole architecture of the system [8].

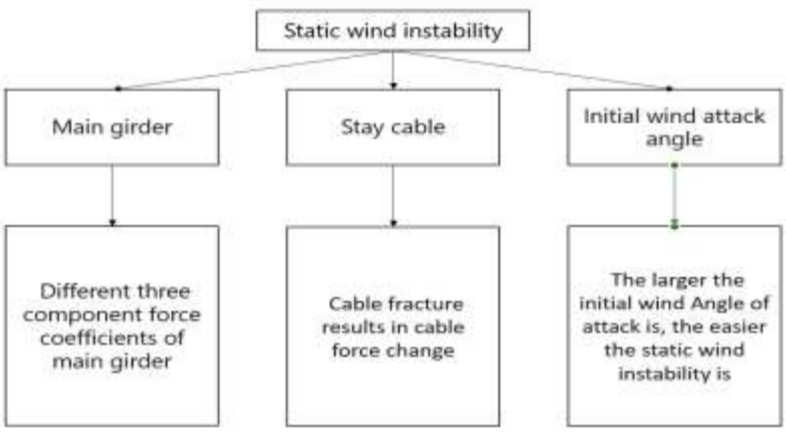


**Figure 2.** Fault tree of static wind instability

Flutter

Bridge flutter refers to the divergent aerodynamic self-excited vibration of the bridge system as a spatial structure under the action of the average wind, which is caused by the continuous absorption of the flowing air from the bridge system than the damping dissipation capacity of the structure. Once a bridge flutters, its structure will suffer devastating damage.

By summarizing the factors of flutter stability of bridge, three factors affecting flutter of cable-stayed bridge are considered [13]:

a) Structural factors. The stiffness of the bridge support and the structural damping of the cable determine the stability of the bridge.

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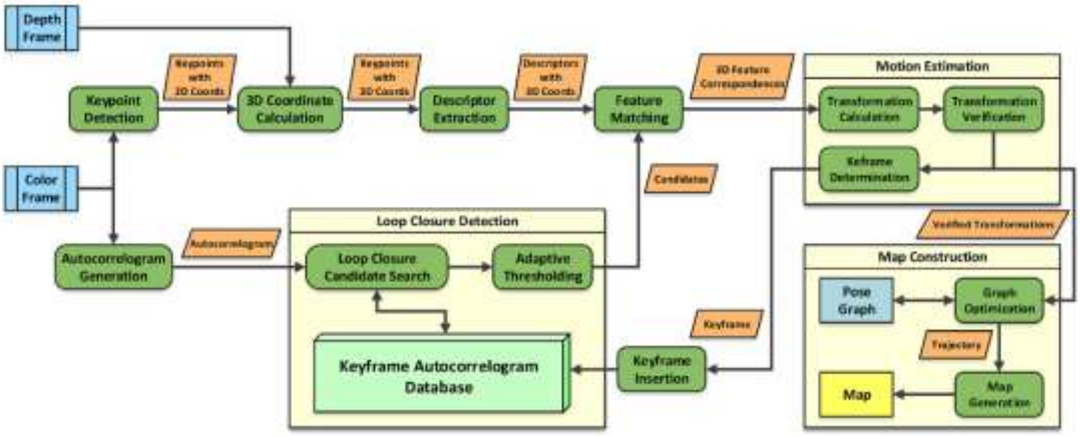
b) Aerodynamic factors. The flutter stability is affected by the geometry of the main girder cross section.

c) Flow factors. The flutter stability is influenced by the wind attack angle.

According to the above analysis results, the fault tree can be drawn to determine the main influencing factors of flutter.

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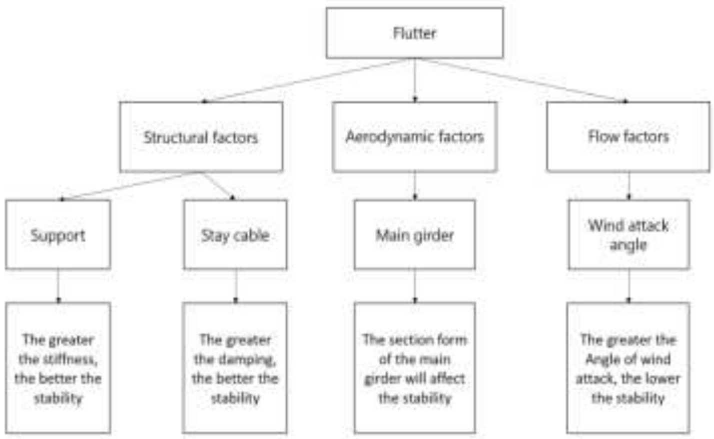


**Figure 3.** Fault tree of flutter

Vortex-induced vibration

Vortex-induced vibration (VIV) is a self-limiting wind-induced vibration with both forced and self-excited characteristics [14]. Although VIV will not damage the structure directly like flutter, the starting wind speed is low, and the continuous vibration will seriously affect the service performance and even lead to the fatigue failure of the structure.

By analyzing the wind-induced vortex vibration response of Bridges, the influencing factors of vortex vibration of cable-stayed Bridges are as followings [15]:

a) Mechanical vibration suppression measures, such as installation of damping devices.

b) Bridge deck ancillary facilities, such as collision barrier, bridge deck wind barrier, etc.

c) Airflow vibration suppression measures, such as flow guide plate, flow suppression plate, etc.

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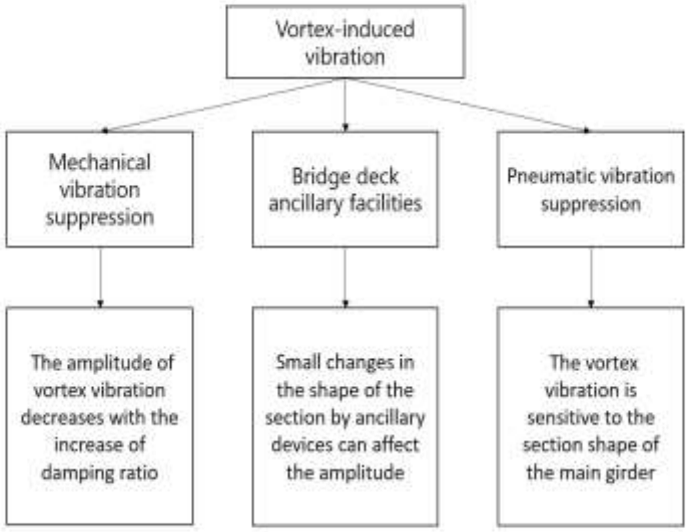


**Figure 4.** Fault tree of VIV

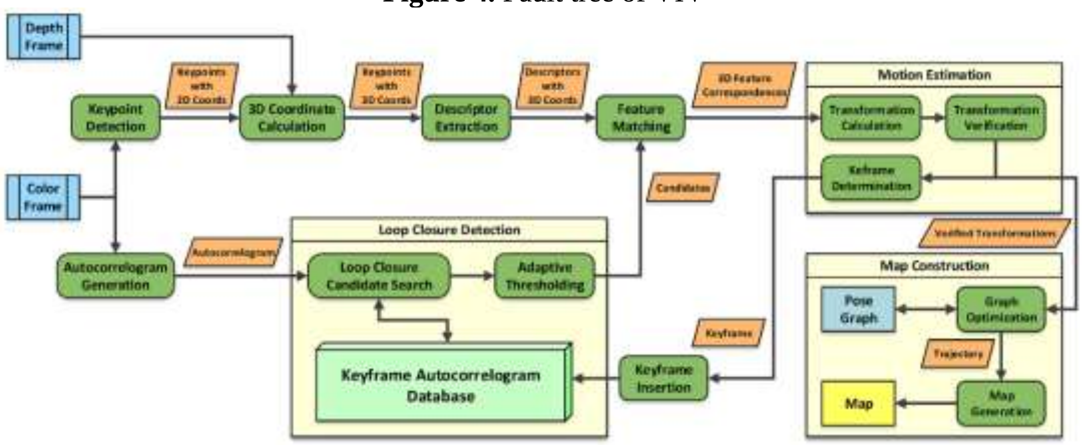


**Figure 3.** Whole architecture of the system [8].

According to the above analysis results, the fault tree can be drawn to determine the main influencing factors of VIV.

*2.2.2. Determine risk assessment criteria.* The fundamental purpose of determining risk assessment criteria is to establish and clarify the probability grade of wind resistance risk of cable-stayed bridge and provide evaluation criteria for risk assessment [16]. In order to reflect the risk level more comprehensively, the following two tables are listed in this paper, and the matrix is used to combine them, so as to form the wind risk resistance criteria of cable-stayed Bridges.

**Table 1** Probability scale

| Possibility of accident | Class of probability | Range of probability |
|---|---|---|
| Almost never happen | I | 0<P<10% |
| Unlikely to happen | II | 10%<P<30% |
| May happen | III | 30%<P<80% |

| | | |
|---|---|---|
| Likely to happen | IV | 80%<P<100% |

**Table 2.** Loss scale

| Description of accident loss | Class of probability | Range of probability |
|---|---|---|
| The impact is small, need to pay attention to the early prevention | 1 | 0<Q<20 |
| Certain degree of safety accidents and economic losses should be taken seriously | 2 | 20<Q<70 |
| Serious safety accidents and economic losses, effective management and technical measures should be taken | 3 | 70<Q<90 |
| Major safety accidents and economic losses, should cancel the established program | 4 | 90<Q<100 |

The occurrence probability of each risk is determined by Table 1, and the degree of risk loss is determined by Table 2. Multiply the risk probability value and risk loss value to get the risk intensity grade matrix, which is shown in Table 3. The risk intensity grade matrix is from the upper left to the lower right, and the risk intensity grade increases gradually, which is used as the evaluation standard of risk grade.

**Table 3.** Risk level

| Risk probability / Risk loss | 0<P<10% | 10%<P<30% | 30%<P<80% | 80%<P<100% |
|---|---|---|---|---|
| 0<Q<20 | D 0~2 | D 2~6 | D 6~16 | C 16~20 |
| 20<Q<70 | C 20~25 | C 25~35 | C 35~60 | C 60~70 |
| 70<Q<90 | C 70~72 | B 72~76 | B 76~86 | B 86~90 |
| 90<Q<100 | B 90~91 | B 91~93 | A 93~98 | A 98~100 |

*2.2.3. Construct Bayesian network model.* The node information of Bayesian network is obtained by combining the fault tree and risk level table of cable-stayed bridge.

Table 4. Bayesian network node information

| a | b | | c | | d | |
|---|---|---|---|---|---|---|
| Main event (Accident happens) | b1 | The main girder is not qualilfied | c1 | The main girder section is not qualilfied | d1 | Different three component force coefficient of main girder section |
| | | | | | d2 | The aerodynamic profile of the main girder section is unqualified |
| | | | | | d3 | The stability of the main girder geometry is too low |
| | | | c2 | The stiffness of the main girder is not qualified | d4 | The span of the main girder is too long |
| | | | | | d5 | The strength of the main girder material is not qualified |
| | | | | | d6 | No regular maintenance of the main girder |
| | | | | | d7 | Lack of ancillary facilities such as storm guardrail |
| | b2 | The stay cable is not qualilfied | | | d8 | Cable fracture rate>10% |
| | | | c3 | The stay cable has low damping | d9 | The strength of the stay cable material is not qualified |
| | | | | | d10 | There is no mechanical vibration suppression |
| | b3 | The support is not qualified | c4 | The stiffness of the support is not qualified | d11 | The structural design of the support is problematic |
| | | | | | d12 | The strength of the support material is not qualified |
| | | | | | d13 | No regular maintenance of the support |
| | | | c5 | High wind attack Angle | d14 | The influence of incoming flow is unstable |
| | | | | | d15 | The elevation of the bridge is too high |
| | | | | | d16 | There is no pneumatic vibration suppression |

Quantify the model parameters of Bayesian network. The parameters of Bayesian network model include the prior probability of root node and the conditional probability of non-root node mentioned above. This paper adopts the method of integrating multi-expert evaluation and big data investigation, which not only absorbs the professional experience of experts, but also corrects the subjective deviation of expert evaluation to a large extent, so as to obtain more professional, comprehensive and objective node parameters of Bayesian network model.

In Table 4, series a is the primary event that occurs. The others are root events that affect the occurrence of the main event, which can be divided into three series b, c and d, according to the degree

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of influence on the main event and the connection between root events. Similar events of series b are the direct causes that can directly cause wind resistance accidents of cable-stayed Bridges. Major problems are not allowed in the actual engineering, and all activities should be stopped immediately if they occur. However, similar events of series e will have a certain impact on the stability or overall stiffness of the structure, but generally will not directly cause bridge accidents, and can be avoided and eliminated through inspection and maintenance.

If we want to know whether the main event occurs or not, or the probability of the main event occurring, we can use equation (1) to calculate from series d to series a successively, and the probability of each root event occurring and the probability of the last main event occurring can be obtained.

### *2.3. Application analysis of Bayesian network model*

Humen Bridge in Guangdong Province is one of the famous cable-stayed Bridges in the southeast coast of China. Taking Humen Bridge as the engineering background, the Bayesian network model established before was used to have a risk assessment of its wind resistance safety.

*2.3.1. Engineering Overview.* Humen Bridge is a cross-sea bridge connecting Guangzhou City and Dongguan City in Guangdong Province, China. It is located over the Lion Ocean of the Pearl River and is an important part of the loop expressway in the Pearl River Delta region.

The structure type is single-span double-hinged cable-stayed bridge, the main cable span is 888 meters, the east span is 302 meters, the west span is 348.5 meters, the main cable span ratio is 1:10.5; The main cable diameter is 687.2 mm (porosity 20%), 678.7 mm (porosity 18%), and the center distance of the main cable is 33 meters. Each main cable consists of 110 cable strands, each of which contains 127 steel wires with a diameter of 5.2 mm. The standard cable strands generally weigh 34.8 tons. The suspension cables of the bridge are 52 mm in diameter, 12 meters apart, and 18 meters away from the center of the tower. The width of the stiffened box girder of the bridge is 35.6 meters, and the height of the beam at the center of the axle is 3.012 meters. The deck is laid with asphalt concrete with a thickness of 6 centimeters. The maximum expansion capacity of the expansion joint at the two bridge towers is 1.5 meters [17].

*2.3.2. Risk assessment.* In this paper, the wind risk safety analysis of Humen Bridge is carried out to verify the engineering feasibility of Bayesian network model, and provide a reasonable risk avoidance scheme for similar engineering.

Determine the conditional probability of each node in the model and use the Bayesian network model for inference operation. The result is shown below.

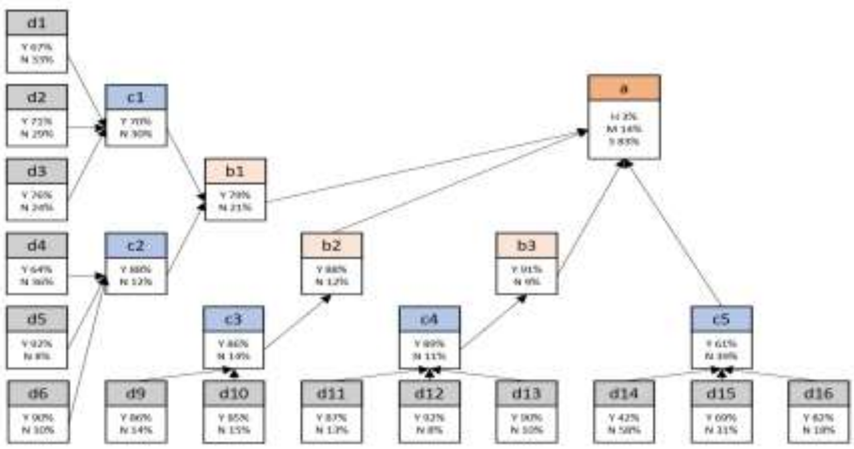


**Figure 5.** Bayesian network derivation diagram

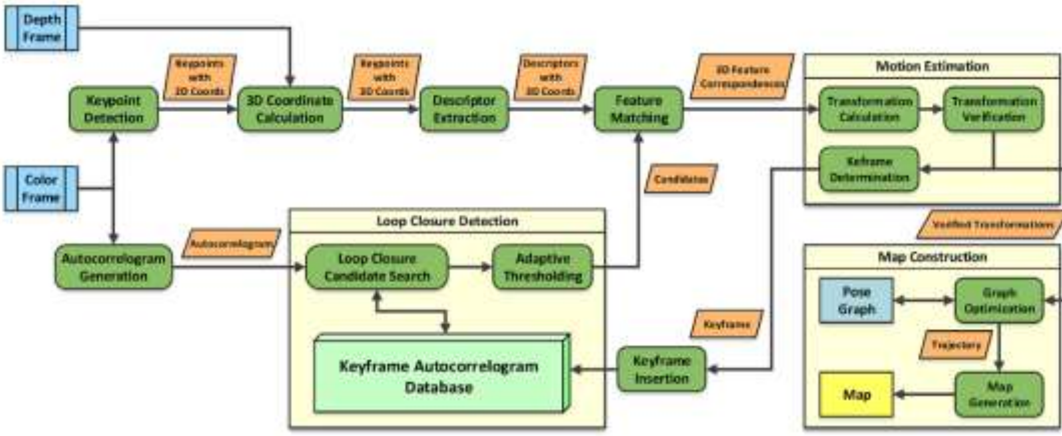


**Figure 3.** Whole architecture of the system [8].

As can be seen from the Bayesian network derivation diagram, the probability of slight loss(S), moderate loss(M) and heavy loss(H) caused by wind in Humen Bridge are 83%, 14% and 3% respectively. Once serious wind-induced accident happens, it will bring great damage to the bridge, and the loss is extremely serious. According to the derivation, the probability of serious accident of Humen Bridge is 3%, which is ‘almost never happen’. At the same time, it is rated as grade D according to the risk intensity matrix, which is an acceptable range. Similarly, a moderate loss is rated as grade D, while a slight loss is rated as grade B.

The above derivation shows that the wind risk of Humen Bridge is generally acceptable, and the overall wind resistance performance of Humen Bridge is good. However, Humen Bridge still has a certain risk of minor accidents, so it is necessary to pay attention to the wind-induced safety of the bridge, strengthen the prevention and inspection work, and carry out regular maintenance.

Considering the actual situation, since the Humen Bridge was opened to traffic in 1997, there has never been a serious bridge accident caused by wind, only a slight vibration caused by VIV. But thanks to continuous maintenance and improvement by engineers, the Humen Bridge has not been structurally damaged and can still be safely used.

Bayesian networks also have strong directional reasoning ability, that is, when the probability of heavy loss is 100%, the factors affecting the wind-induced safety of the bridge are analyzed.

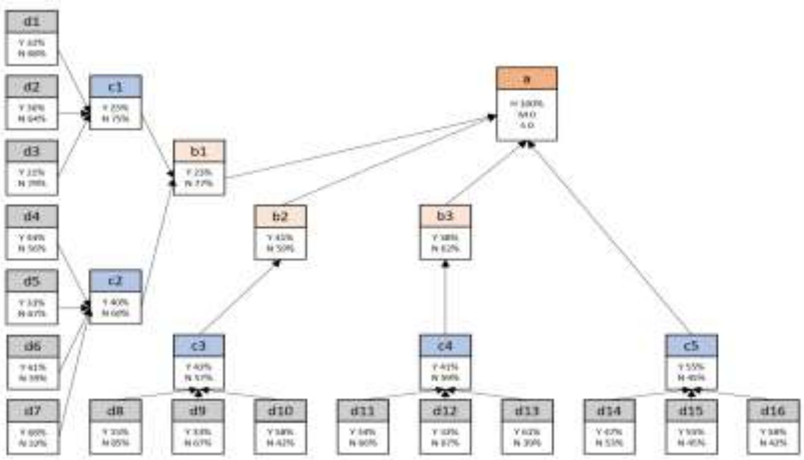


**Figure 6.** Reverse reasoning results

According to the reverse reasoning results in the figure above, when Humen Bridge suffers serious losses, the most direct impact is the problem of the b1 node, namely the main girder. Therefore, the unqualified main girder is an important reason for the serious loss of the bridge. As for the next level,

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c1 has the greatest impact on b1 nodes, and its probability is 75%. Similarly, the main reason for the unqualified main girder section is the low stability of the main girder section.

But fortunately, these reasons are taken into account and avoided as much as possible during the construction of the bridge, so Humen Bridge has never had a serious accident.

*2.3.3. Summary.* From the results of Bayesian network analysis and the actual engineering situation, the analysis of this model is basically consistent with the reality. It can not only effectively predict the probability of wind-induced risk accidents of bridges, but also analyze the causes of existing accidents, to avoid these factors in the future construction and maintenance of the bridge engineering.

## 3. Conclusion

### *3.1. Main conclusions*

Due to the uncertainty of wind loads encountered by cross-sea Bridges, it is of great significance to establish a unified and accurate safety measurement and judgment mechanism for anti-wind risks of cable-stayed Bridges for risk prevention and control and emergency management of such Bridges [18]. Based on the Bayesian network model, this paper proposes a method to evaluate the wind resistance risk of cable-stayed bridge, and gives the specific modeling and application steps. The main research results are as follows:

The wind risk assessment system of cable-stayed bridge is established, including the wind risk assessment process of cable-stayed bridge, risk source identification method, wind safety assessment method of cable-stayed bridge, and the operation process of wind risk assessment of cable-stayed bridge is given.

The risk factors of cable-stayed bridge and Bayesian network nodes are integrated, and the event and causality in fault tree are mapped in Bayesian network. It shows that Bayesian networks play an important role in risk assessment.

The safety assessment system of wind-resistant risk of cable-stayed bridge based on Bayesian network enables us to assess the risk of bridge from a quantitative perspective, and the prediction results are more accurate, which can provide method reference for similar engineering.

### *3.2. Expectations*

Based on the existing risk assessment theory and method, this paper firstly studies the wind hazard sources of cable-stayed bridge and draws the corresponding accident tree. Secondly, according to the standard of previous risk assessment, the risk strength level of cable-stayed bridge is determined. Then the events in the accident tree correspond to the nodes of the Bayesian network one by one, and the parameters of the Bayesian network are quantified according to the big data and expert experience. Finally, we have a quantitative wind risk assessment model for cable-stayed Bridges based on Bayesian network.

However, whether in theoretical research or practical application, there are many shortcomings in this paper, and a lot of work needs to be done, which are mainly reflected in the following aspects:

The node data of Bayesian network model is determined by means of big data and expert survey. How to further improve the quality of sample data is the key to ensure that the model plays its role.

At present, many world Bridges have accumulated a large amount of monitoring data, which need to be further applied in the risk assessment of Bridges.

The calculation process of this model is too complicated, it is better to make relevant software to assist the calculation.

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