Safety Risk Analysis of Bridge Rhombic Hanging Basket Construction Based on WBS-RBS and Rough Set Theory

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Abstract: Because of its simple structure, light static load and no balance-weight, the rhombic hanging basket has become one of the most widely used forms in bridge hanging basket construction. In the construction process of rhombic hanging basket, there are often high risks and hidden dangers, which may cause serious engineering accidents and losses. If we can analyze these risks in the early stage of the construction of hanging basket, we can not only provide security for the construction process, but also provide basis for the construction safety management. In this paper, a comprehensive evaluation model is established by using Work Breakdown Structure- Risk Breakdown Structure and rough set theory. This model uses WBS-RBS coupling to form the association between the construction risk and the operation activities of the hanging basket, and the risk decomposition matrix is constructed to identify the risk of the whole hanging basket construction process in detail, and each risk factor is corresponding to each bottom work package. Then, rough set theory is used to determine the weight of risk in each underlying work package. Finally, the risk degree of each operation unit in the construction process is sorted according to the weight value of the risk contained, and then the high-risk links in the construction process of hanging basket can be clearly understood, so as to provide basis for construction risk management.

1. Introduction
As one of the main forms of hanging basket in bridge construction, the rhombic hanging basket is widely used in the construction process of cast-in-place continuous rigid frame bridge. Now its construction technology is becoming more and more mature. However, the construction facilities of bridge diamond hanging basket are huge and complex, which are mostly high-altitude operations. During the construction period, collapse accidents and casualties occur from time to time. In view of the problem of high safety risk and serious accident consequences in the rhombic hanging basket construction, it is particularly important to analyze and control the risk in its construction process. At present, there are few studies on risk assessment of hanging basket construction in China, and most of them focus on the following two aspects. First, most of the research focuses on the mechanical properties of the hanging basket itself. Through the analysis of the hanging basket’s force condition, the design structure and construction technology of the hanging basket are optimized. For example, Jin Huifu [1], a domestic scholar, uses the finite element software MIDAS/civil to carry out simulation analysis, and finds out the corresponding positions and load combinations of the cradle structure with large stress or deformation. Wu Yuexing [2] proposed a new type of triangle truss hanging basket, and analyzed its stress relationship with Midas civil and Midas fee, which confirmed the rationality and feasibility of the hanging basket. Second, the research on the risk of hanging basket is mainly qualitative evaluation.
Wang La [3], a scholar, explores the process of accident evolution by analyzing the connotation and connection of safety risks and hidden dangers in basket construction. However, the construction safety of bridge hanging basket is not only related to the stress and construction technology, but also closely related to the construction site operators and management system. The risks in the construction process of hanging basket have the characteristics of diversity and changeability, so the risk identification and evaluation in the construction should be comprehensive. In addition, the quantitative analysis, which shows the risk by objective value, is more intuitive and persuasive than the simple qualitative analysis. Work Breakdown Structure- Risk Breakdown Structure is a kind of analysis method that can grasp the overall situation of engineering risk and overcome the failure of other methods to take into account the details of engineering safety risk. It can also calculate the risk weight of each activity unit with rough set theory. In this way, we can not only comprehensively analyze the risks in the whole construction process, but also calculate the weight of each risk unit quantitatively. Taking the rhombus hanging basket used in the cantilever cast-in-place construction of the main bridge of Hongnongjian River Bridge as an example, this paper uses WBS-RBS [4] and rough set theory to build an evaluation model, and analyzes the safety and risk problems of the rhombus hanging basket in the construction.

2. Risk analysis model of bridge hanging basket construction

2.1. WBS-RBS risk matrix method
WBS (Work Breakdown Structure) and RBS (Risk breakdown structure) is an important means of project management [5]. David Hillson, a PMI expert, is the first American expert who study the risk management based on WBS-RBS matrix. Based on WBS-RBS matrix, the research on the construction risk of hanging basket has the following advantages: ① it can systematically sort out the risk laws of the construction project of the hanging basket, covering the possible risks in the construction, and effectively avoid the risk omission by identifying each WBS node according to the RBS; ② risk classification and risk factors are more clear and systematic after classification and level division, avoiding the confusion of risk division, and facilitating risk planning response, data processing, evaluation analysis and experience accumulation[6]. There are three steps to establish WBS-RBS matrix: ① build WBS, the whole project is divided into several independent work units from top to bottom; ② build RBS, the possible risks of the whole project are decomposed layer by layer until the attributes of various risks are similar; ③ The WBS-RBS matrix is established by taking the lowest job package set of WBS as the column of matrix and the lowest risk factor set of RBS as the row of matrix. In WBS-RBS matrix, the intersection of row and column is the risk point. For each risk point, judge whether it exists and evaluate the possibility of occurrence one by one.

2.2. LEC risk assessment method
LEC evaluation method is proposed by K.J. Graham and K.F. Ginny. It is a semi quantitative safety evaluation method for hazard sources in potentially hazardous working environment [7]. This method uses the product of three factors related to the system risk to evaluate the risk of the project. The three factors are L (likelihood, the possibility of accidents), E (exposure, the frequency of people exposed to dangerous environment) and C (criticality, the possible consequences of accidents). In order to simplify the evaluation process, the semi quantitative method is adopted, which divide the LEC into different grades and assigned values respectively according to the previous experience and estimation, and then the product D (danger) of the three scores is used to evaluate the risk of operation conditions. Namely: $D = L \times E \times C$

The higher the value of D, the more dangerous the system is, and it is necessary to increase safety measures, or change the possibility of accidents, or reduce the frequency of human exposure to dangerous environment, or reduce the accident loss until it is adjusted to the allowable range.
2.3. Rough set theory
In this paper, rough set theory is used to determine the weight of risk factors in the construction of bridge hanging basket. Rough set theory was first proposed by Z. Pawlak, a Polish mathematician, in the early 1980s. As a natural method of data mining or knowledge discovery, rough set theory can effectively analyze and process incomplete, imprecise and inconsistent data, discover hidden knowledge and reveal potential laws without providing any prior information beyond the data set that the problem needs to be processed. At present, it is an effective and objective mathematical tool to describe or deal with problems[8].

Basic concept 1 (Information System)

An information system is a quadruple \((U, Q, V, f)\)

- \(U\) is a set of objects
- \(Q\) is the attribute set (including condition attribute \(C\) and decision attribute \(D\))
- \(V\) is the range of the attribute
- \(f\) is a mapping that reflects the values between sets of objects

Basic concepts 2 (Indiscernible relations and basic sets)

Indistinguishable relation \(IND(P)\) / equivalent relation: for any attribute set \(P\), indistinguishable relation is represented by \(IND\), which is defined as follows:

\[
IND(P) = \{ (x, y) \in U \times U : f(x, a) = f(y, a), a \in P \}
\]

(1)

Indiscernible relation is equivalent relation on \(U\)

Basic Set: a set of indistinguishable objects in a domain, which is the particle of domain knowledge.

Basic concepts 3 (Lower approximation of set)

Let \(U\) is a discourse domain (nonempty object set), \(I\) is a set of equivalence relations of \(U\), then The lower approximation of set \(X\) with respect to \(I\) is the largest set of objects that must belong to \(X\) according to existing knowledge, sometimes called the positive region of \(X\), and expressed as \(POS(X)\).

\[
l_i = (X) = \{ x \in u : I(x) \subseteq X \}
\]

(2)

Dependability of attribute

The degree of dependence of decision attribute \(D\) on condition attribute \(C\) is defined as follows:

\[
r_c(D) = \frac{POS_c(D)}{|P|}
\]

(3)

\(POS_c(D)\) is the positive area of the attribute set \(C\) in \(U/IND(D)\)

Importance of attributes

The importance of adding attribute \(a\) to \(C\) to classification \(U/IND(D)\) is defined as follows:

\[
SGF(a, C, D) = r_c(D) - r_{c\{a\}}(D)
\]

(4)

2.4. Cause model of construction risk of hanging basket

According to the characteristics of China's hanging basket construction project and the actual situation of construction management, this paper constructs the risk cause model of bridge hanging basket construction, which describes the risk occurrence mechanism from the perspective of risk analysis and management by referring to Bode's accident cause and effect chain theory [9], as shown in figure 1 below.
3. Analysis of engineering example

3.1. General situation of the engineering
The rhombus hanging basket is used for the cantilever cast-in-place beam construction of the main bridge of Hongnongjian River Bridge and it adopts the prestressed concrete rigid frame continuous-composite system. The standard span of the main bridge is \((87 + 6 \times 160 + 87)\) m which adopts single box single chamber box section, and the height of the box girder and the thickness of the bottom plate are all changed by parabola of order 1.8. The height of the root beam at the center line of the box girder is 1050cm, and the height of the mid span beam is 400cm, and the width of the top plate is 1225cm, and the width of the bottom plate is 650cm, and the thickness of the top plate is 30cm, and the thickness of the bottom plate is 120cm, and the thickness of the web is 55 ~80cm. Section 0 of the box girder is 1400cm long. The single "T" of the box girder is cast in 18 cantilever sections, with the section length of 6x3.5 + 6x4m + 6x4.5m and the side span cast-in-place section length of 5.6m. The closure section of middle and side span is 2.0m. The main bridge is closed in the following order: the fourth and fifth spans of the main bridge \(\rightarrow\) the first and eighth spans of the main bridge \(\rightarrow\) the second and seventh spans of the main bridge \(\rightarrow\) the third and sixth spans of the main bridge.

3.2. Establish WBS-RBS matrix to identify the construction risk of hanging basket

3.2.1. Build WBS. The construction process of bridge hanging basket can be divided into five stages according to the whole operation life cycle, namely: hanging basket installation, hanging basket preloading, hanging basket use (including formwork engineering, reinforcement engineering, concrete engineering, prestressed engineering, etc.), hanging basket walking and hanging basket removal. Then, according to these five stages, the WBS tree of hanging basket construction is obtained, as shown in Figure 2.

3.2.2. Build RBS. According to the risk cause model of bridge hanging basket, this paper analyzes the risk of the whole process of hanging basket construction from four aspects: personnel risk, environmental risk, material and machine risk and technical risk, and further subdivides it into 19 independent risk forms to form RBS tree, as shown in Figure 3.
3.2.3. Establish RBM matrix to identify construction risk of bridge hanging basket. The risk decomposition matrix is constructed with the lowest risk of the construction risk decomposition tree of the bridge hanging basket as the column and the lowest work unit of the work decomposition tree as the row. The intersection of row and column is the risk point. For each risk point, judge whether it exists one by one. If it exists, fill 1 in the corresponding position in the matrix, otherwise fill 0 [10]. However, considering the multidimensional characteristics of risk, the traditional risk assessment method is no longer applicable. In this paper, LED risk evaluation method is used to evaluate the risk of bridge hanging basket construction. The values of L, E, C and D can refer to the quantitative standard of LEC operation risk proposed by Graham and Ginny. The results of LEC risk evaluation are used as evaluation indexes to fill in the RBM matrix, and the results are shown in Table 1.

![Figure 2: Work breakdown tree of bridge hanging basket (WBS)](image-url)
Figure 3  Risk breakdown tree of bridge hanging basket (RBS)
3.3. Risk weight determined by rough set theory

In this paper, through the expert scoring, a total of 45 scoring tables are received. Through the discretization of these data, a decision table based on rough set theory is obtained. Then, input the processed data into ROSETTA software, and use Johnson's algorithm to optimize the risk evaluation index, and finally get 30 groups of effective data. This paper takes the risk of human factors in $W_8$ concrete work unit as an example, and uses rough set theory to determine the weight of risk factors. The universe of discourse $U = \{x_1, x_2, ..., x_n\}$, conditional attribute $C = \{R_1, R_2, R_3, R_4\}$, decision attribute $D = \{1, 2\}$, 1 represents the risk that can be taken, and 2 represents the risk that cannot be taken, $\nu = \{1, 2, 3, 4\}$, the values 1,2,3,4 represent low risk, medium risk, high risk and serious risk respectively, and the higher the value of risk degree is, the more rectification is needed in the engineering. Table 2 shows the risk assessment table of work unit of $W_8$.

| Table 1 | LEC evaluation table of WBS-RBS coupling matrix |
|---------|-------------------------------------------------|
| $RBS$ decomposition system | $WBS$ decomposition system | Construction work of bridge hanging basket $W$ |
| $R_1$ | $W_1$ $W_2$ $W_3$ $W_4$ | Hanging basket installation $W_1$ $W_2$ $W_3$ $W_4$ | HBP $W_5$ | Hanging basket use $W_6$ $W_7$ $W_8$ $W_9$ | HBR $W_{10}$ $W_{11}$ $W_{12}$ $W_{13}$ |
| $R_2$ | 108 54 126 108 | 126 135 126 0 | 0 0 0 0 | 126 135 |
| $R_3$ | 54 27 54 126 | 54 27 18 180 54 | 54 54 54 108 | 54 60 |
| $R_4$ | 135 108 108 54 | 60 126 54 60 126 | 108 135 126 270 | 126 135 |
| $R_5$ | 18 18 54 18 | 108 108 108 42 60 | 0 0 0 0 | 108 108 |

Note: HBP (Hanging basket preloading); HBR (hanging basket removal); Table 1 corresponds to figure 2 and figure 3.
The data domain in Table 2 is divided into equivalent classes according to condition attribute and decision attribute:

\[
U/D = \{(1,4,6,7,8,10,13,14,17,18,20,21,23,24,27,29),(2,3,5,9,11,12,15,16,19,22,25,26,29,30)\}\qquad (5)
\]

\[
U/C = \{1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30\}\qquad (6)
\]

On the division of domain equivalence classes after removing one condition attribute in turn:

\[
U/(C - C_1) = \{(1,4,22),(2,27),(3,13),(5,26),(6,23),(7,14,23),(9,26,30),(11,12,13,15,16,19,20,21,22,23,24,25,26,27,28,29,30)\}\qquad (7)
\]

\[
U/(C - C_2) = \{(7,8,9,(10,12,30),(11,14),(15,16,25),(17,24,28),(18,20),(19,21,29)\}\qquad (8)
\]

\[
U/(C - C_3) = \{(1,2,3,(4,29),(5,8),(6,7,19,26),(9,23),(10,11,12,13),(14,26),(15,28),(16,17),(19,20,21,22),(24,25,27)\}\qquad (9)
\]

\[
U/(C - C_4) = \{(1,2,8),(3,4,24,27),(5,10),(6,8),(7,14,23),(9,26,30),(11,12,13,15),(16,17,22),(18,21),(19,20),(25,29)\}\qquad (10)
\]

Positive domain of decision attribute under each condition attribute:

\[
POS_c(D) = \{1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30\}\qquad (11)
\]

\[
POS_{c-C_1}(D) = \{5,26,6,23,7,8,9,11,14,15,16,25,17,24,28,18,20,19,21,29\}\qquad (12)
\]

\[
POS_{c-C_2}(D) = \{1,2,3,6,10,11,12,13,19,20,21,22,27\}\qquad (13)
\]
\[ POS_{c_1}(D) = \{3, 4, 24, 27, 6, 7, 14, 23, 9, 26, 30, 11, 12, 13, 15, 16, 18, 21, 19, 20, 25, 29\} \]  
\[ POS_{c_2}(D) = \{1, 3, 29, 30, 4, 14, 5, 11, 15, 7, 18, 24, 8, 28, 9, 10, 16, 17, 20, 19, 21, 23, 27, 22, 25, 26\} \]  

The approximate accuracy of each condition attribute with respect to the decision attribute:

\[ \gamma_c(D) = \frac{\text{POS}_c(D)}{|U|} = 1 \]  
\[ \gamma_{c-e_1}(D) = \frac{\text{POS}_{c-e_1}(D)}{|U|} = \frac{20}{30} \]  
\[ \gamma_{c-e_2}(D) = \frac{\text{POS}_{c-e_2}(D)}{|U|} = \frac{14}{30} \]  
\[ \gamma_{c-e_3}(D) = \frac{\text{POS}_{c-e_3}(D)}{|U|} = \frac{23}{30} \]  
\[ \gamma_{c-e_4}(D) = \frac{\text{POS}_{c-e_4}(D)}{|U|} = \frac{26}{30} \]

The importance of each condition attribute to the decision attribute:

\[ SGF(C, C, D) = r_c(D) - r_{c-e_i}(D) = \frac{10}{30} \]  
\[ SGF(C, C, D) = r_c(D) - r_{c-e_i}(D) = \frac{16}{30} \]  
\[ SGF(C, C, D) = r_c(D) - r_{c-e_i}(D) = \frac{7}{30} \]  
\[ SGF(C, C, D) = r_c(D) - r_{c-e_i}(D) = \frac{4}{30} \]

After normalizing the data, the weight values are as follows:

\[ W_i = 0.2703, W_i = 0.4324, W_i = 0.1892, W_i = 0.1081 \]

Then according to the above algorithm, we can get the weight value of other risks in the operation, and sort each activity according to the weight value, as shown in Table 3:

| Table 3   Weight value and risk value of risk factors of concrete engineering |
|---------------------------------|----------------|----------------|----------------|----------------|
| criterion | influence factor | weight | Total weight | risk value | Sorting |
| Personnel (0.4359) | R1 | 0.2703 | 0.1178 | 108 | 2 |
| | R2 | 0.4324 | 0.1885 | 180 | 1 |
| | R3 | 0.1892 | 0.0825 | 60 | 3 |
| | R4 | 0.1081 | 0.0471 | 42 | 4 |
| environment (0.1026) | R1 | 0.0612 | 0.0063 | 6 | 3 |
| | R2 | 0.3469 | 0.0356 | 36 | 2 |
| | R3 | 0.5918 | 0.0607 | 60 | 1 |
| Materials \ machines (0.2564) | R1 | 0.2294 | 0.0588 | 54 | 2 |
| | R2 | 0.2018 | 0.0517 | 42 | 3 |
| | R3 | 0.4862 | 0.1247 | 108 | 1 |
| | R4 | 0.0826 | 0.0212 | 18 | 4 |
| Technology (0.2051) | R1 | 0.0891 | 0.0183 | 18 | 4 |
| | R2 | 0.5347 | 0.1097 | 108 | 1 |
| | R3 | 0.2970 | 0.0609 | 60 | 2 |
| | R4 | 0.0792 | 0.0162 | 27 | 3 |
It can be seen from the table that $R_{12}$ Poor management, $R_{13}$ Poor maintenance, $R_{14}$ Poor operation of operators, $R_{15}$ Unqualified construction materials, $R_{16}$ Violation of construction sequence or standard are the main risks in concrete construction $W$, and $R_{17}$ poor maintenance is the high risk. In addition, $R_{18}$ Operators fall from height, $R_{19}$ Construction smoke and dust, $R_{20}$ Improper use of temporary electricity, $R_{21}$ Falling of construction articles, $R_{22}$ Unreasonable construction technology and scheme should also be paid special attention.

4. Conclusion

In this paper, WBS-RBS method is used to identify the risk of bridge rhombus hanging basket construction project, and the coupling matrix is constructed. Finally, the weight of each risk is determined by rough set theory, which gives a quantitative value to each risk, and then the importance of each risk can be ranked according to the value. Moreover, the results of risk analysis are in good agreement with the actual situation of the project construction, which shows that the reliability of the method is high. The paper proves that the risk assessment model based on WBS-RBS and rough set theory can be well applied to the risk analysis of bridge rhombic hanging basket construction, so as to provide a strong basis for the risk management of bridge hanging basket construction.

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