Research on Risk-Based Assessment and Maintenance Priority Ranking of Bridge Components

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Abstract. This study explores a risk-based approach for the assessment and maintenance prioritization of bridge components, utilizing the latest inspection results from 2023. A comprehensive risk analysis framework is established to evaluate the risk levels of various bridge components, enabling the effective allocation of inspection and maintenance resources. The findings demonstrate that risk analysis offers significant advantages in identifying critical components, supporting preventive maintenance, and reducing the likelihood of future sudden failures.

Keywords: Bridges inspection; condition evaluations; risk assessment

1 Introduction

Bridges are essential nodes within highway transportation networks. With the rapid development of China's highway infrastructure, the number of highway bridges has steadily increased. By the end of 2023, the total number of bridges reached 1.0793 million, spanning a cumulative length of 95.2882 million linear meters, making it the largest highway bridge system in the world. The system has now entered a critical period of intensive maintenance due to the following factors [1]. (1) Aging Infrastructure: Nearly 30% of bridges are over 20 years old, and 15% of the bridges on national and provincial highways have been in service for more than 30 years. (2) Structural Deficiencies and Increased Traffic Load: Many early-constructed bridges suffer from design and construction flaws. Combined with the heavy traffic demands of today, most of these bridges operate with existing deficiencies, leading to the accumulation of safety risks. To ensure that bridges can continue to function safely within the highway network, it is essential to conduct high-quality maintenance that guarantees their structural safety. Inspection serves as the foundation of all maintenance activities. The guiding principles for bridge maintenance in China are outlined as "prevention and treatment, scientific maintenance, safe operation, and traffic flow assurance" The Specifications for Maintenance of Highway Bridges and Culverts（JTG 5120-2021）classifies bridge inspections into five categories: initial inspection, routine patrol, frequent inspection, periodic inspection, and special inspection. Among these, periodic inspections play the most

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critical role, as they provide a comprehensive assessment of a bridge's technical condition. According to the code, bridges classified under Maintenance Level I must undergo periodic inspections at least once a year, while those under Maintenance Levels II and III must be inspected every three years. This calendar-based inspection approach is widely used internationally due to its simplicity and practicality. It reflects the global lack of consensus on the relationship between bridge degradation and safety. However, the limitations of this periodic inspection model are also apparent. It does not account for the service life, deterioration process, or the impact of defects on structural safety.

As a result, well-maintained, newly constructed bridges may be over-inspected, while deteriorating bridges may not receive sufficient inspection. According to relevant studies, there is a significant gap in highway maintenance funding in China. Given the insufficient overall budget, it is imperative to explore new methods for determining the intervals between periodic inspections. Adjusting inspection frequencies based on the safety requirements of individual bridges will help optimize the use of resources over time and address risks at different stages of the bridge's life cycle. This approach is crucial for enhancing the safety and functionality of the entire bridge system. This paper proposes a bridge condition evaluation method that comprehensively analyzes the relationship between component degradation and safety. It integrates the principles of China's existing Specifications for Maintenance of Highway Bridges and Culverts (JTG 5120-2021) and the Standards for Technical Condition Evaluation of Highway Bridges (JTG/T H21-2011), while drawing on risk-based bridge inspection practices from the United States. The method conducts risk assessments for individual bridge components to guide inspection efforts more effectively.

2 Research Progress Domestically and Internationally

When developing a bridge inspection plan, the primary considerations are the inspection methods and frequencies. On one hand, fixed inspection intervals determined based on past engineering experience lack sufficient justification. Some studies have not regarded fixed inspection intervals as the most effective approach for bridge inspections [2]. For instance, applying the same fixed inspection intervals for bridges that have been in service for many years and newly constructed bridges is often viewed as an unnecessary waste of inspection resources. Shorter inspection intervals result in more frequent inspections, which may introduce unnecessary risks to road traffic and safety. Therefore, implementing variable inspection intervals based on the condition of the bridge may better align with practical needs and reduce the demand for inspection resources. On the other hand, the current practice of using the same inspection methods throughout the entire lifecycle of a bridge may not be optimal. If the degradation patterns of a bridge over its service life could be understood, different inspection methods could be adopted at various stages. Thus, Therefore, in the analysis of the effectiveness and costs of inspecting bridges with varying degrees of structural damage, a risk-based inspection method has been introduced to determine inspection priorities, thereby extending the lifespan of the structure [3].

In bridge structures, RBI considers both the probability and consequences of failure in terms of usability and safety, distinguishing it from reliability-based approaches. Unlike reliability-based methods, which focus primarily on the timing of damage occurrence, risk-based bridge inspections also account for the consequences of such damage [4]. This approach allows inspection resources to be directed toward components with severe damage and significant consequences. After each new inspection, the condition of components is reassessed based on the inspection data to determine new inspection priorities and intervals [5]. M. Parr et al [6]. proposed an alternative to traditional calendar-based inspection methods. Their approach relies on expert judgment and relevant analyses to assess bridge conditions and link the results to inspection intervals. However, this method does not completely replace or eliminate routine bridge inspections, leaving some issues related to scheduled inspections unresolved. To address the limitations of conventional inspections, G. Washer et al [7]. developed a simplified RBI method. This approach integrates risk analysis into expert judgments and uses straightforward calculations to assess the probability of specific types of damage occurring over a given period, as well as their potential consequences, with a focus on bridge safety. The inspection intervals are then determined based on these evaluations. This method requires an expert team to assess both the probability of damage occurrence and the associated consequences to evaluate safety and maintainability [8]. Simultaneously, damage is prioritized based on its importance, with risk defined as the product of the probability of occurrence and the related consequences within a given timeframe, which helps set inspection intervals [9]. To minimize subjectivity and variability in expert judgments, Nasrollahi Massoud [10] introduced a statistical approach. This method utilizes scoring data from 20 years of routine bridge inspections to calculate the average duration and standard deviation for which bridge components remain in a particular condition, providing a quantitative historical analysis. Research has shown that the extended inspection intervals under RBI do not lead to sudden damage or abrupt changes in bridge ratings during the interval periods [11].

In summary, a risk-based approach to bridge inspection can allocate resources more effectively. By further considering the consequences of damage and dynamically adjusting priorities and intervals based on inspection results, inspection resources can be focused on critical areas. Studies have shown that risk-based inspections can extend the inspection intervals without compromising the safety of the bridge.

3 Comparison of Chinese and American Standards

3.1 U.S. Bridge Inspection Standards

The types of bridge inspections in the U.S. are divided into seven categories: initial inspection, routine inspection, service inspection, in-depth inspection, fracture-critical inspection, underwater inspection, and special inspection. In the 2022 release of the National Bridge Inspection Standards (NBIS), a formal risk-based inspection interval standard for routine bridge inspections was introduced. Additionally, both simplified and stricter risk-based interval methods were established. This approach evaluates bridge reliability and safety by assessing the likelihood of damage, related deterioration mechanisms, and potential consequences, which helps determine the inspection requirements and improves overall bridge safety. Under the simplified risk assessment method, an inspection interval of up to 48 months is permitted, while the more stringent method, assessed by the RAP (Risk Assessment Panel), allows a maximum inspection interval of 72 months.

The U.S. risk-based bridge inspection method first requires forming a risk assessment panel composed of various experts. This panel uses engineering principles and typical deterioration models to evaluate the reliability of bridges and assess the potential consequences of damage, analyzing inspection needs. The process is completed in three steps:

First, over a specific period, the likelihood of damage to bridge components is estimated based on potential deterioration patterns, design attributes, load conditions, and other relevant factors. This likelihood is categorized into four occurrence factors, representing the probability of component failure, ranging from low (very unlikely) to high (very likely).

Then, both safety and maintainability aspects are considered when evaluating the consequences of damage. Hypothetical failure modes are used to determine possible consequences, including direct and short-term impacts. Direct consequences involve the integrity of the structure and public safety, such as whether the structure remains stable and the traveling public remains safe. Short-term consequences refer to serviceability and the impact on traffic flow—whether damage limits the bridge's accessibility for public use. The consequences are classified into four consequence factors, ranging from low (minimal impact on serviceability) to severe (bridge collapse with potential loss of life).

Finally, a simple risk matrix (Table 1) is created by combining the occurrence and consequence factors to determine inspection priority and frequency, with intervals ranging from 12 to 96 months. These intervals ensure that the probability of severe damage remains low throughout the inspection period. Bridges with higher damage likelihoods receive multiple inspections before major risks can materialize. As the consequence factor increases, the inspection interval is further reduced to ensure the structure maintains a higher safety margin.

Table 1. Risk matrix indicating the inspection interval basedon OF and CF of a bridge[7].

Occurrence factor	High	48	24	24	12
	Moderate	48	48	24	24
	Low	72	72	48	24
	Remote	96	72	48	48
		Low	Moderate	High	Severe
		Consequence factor			

3.2 China's Bridge Inspection Standards

The 2021 edition of the Specifications for Maintenance of Highway Bridges and Culverts classifies bridge inspections into five categories: initial inspection, routine patrol, frequent inspection, periodic inspection, and special inspection. Following the principle of "focusing on key aspects, maintaining the general condition, and adopting differentiated approaches," bridge maintenance inspections are divided into three levels (I, II, and III) based on the scale and importance of the bridge. For different maintenance levels, the new standard refines the inspection schedule and maintenance resource allocation to ensure effective management. Compared to the 2004 edition, the updated standard introduces differentiated management of inspection frequency and content, initially incorporating risk-based inspection intervals to enhance the efficient use of maintenance resources.

Compared to regular bridge inspections in the U.S., China's periodic inspections align closely in terms of purpose and requirements, but differences exist in how inspection intervals are determined. Additionally, bridge inspections in China face several constraints, particularly in areas with limited accessibility or poor connectivity, where visual inspections alone make it challenging to detect or identify certain types of defects. The reliance on inspectors' subjective experience often limits inspections to visible surface damage, primarily focusing on components with significant deterioration. Moreover, due to the subjectivity involved in assessing visual damage, it is difficult to consider how component failures might impact the overall structure when conducting qualitative evaluations of deterioration. Adopting risk-based methods allows for more precise assessments of bridge conditions identified through visual inspections, optimizes inspection intervals, and establishes inspection priorities. This enhances the scientific approach and efficiency of maintenance and management efforts.

4 Risk-Based Bridge Condition Evaluation Method

In China, periodic inspections are primarily based on visual assessments. During these inspections, the common defects and damage conditions of bridge components, as well as the effectiveness of maintenance efforts, are evaluated. The technical condition rating of a bridge is determined by calculating weighted scores across three sections: the superstructure, substructure, and deck system. The results are categorized into five levels, reflecting the overall condition of the bridge. These periodic inspections serve as the main basis for formulating maintenance and repair plans. Risk-based bridge evaluation methods introduce a new perspective, building upon the results of periodic inspections while incorporating elements from the U.S. risk-based bridge inspection standards. This approach not only considers the current condition of the bridge but also analyzes the degradation state of components and the consequences of potential failures. The impact of these failures on the safety of the entire structure is evaluated to enhance the foresight of maintenance activities. The evaluation process includes four risk levels, reflecting the potential impact of component failures on the structural safety and serviceability of the bridge, helping to prioritize inspection and maintenance efforts effectively.

Figure 1 presents a flowchart of the risk-based bridge condition evaluation method. This approach involves four main steps: First, each component of the bridge is classified into five consequence factors based on the impact of its failure on the overall structural safety. Next, the technical condition ratings obtained from periodic inspections (ranging from 1 to 5) are incorporated. Then, a risk matrix is applied to evaluate each component, assigning it a specific risk level. Finally, the bridge maintenance and inspection priorities are determined based on the number of components within different risk levels. Since this method aims to remain straightforward and efficient for application across the entire road network, additional investigations may be required for bridges with unique structural characteristics.

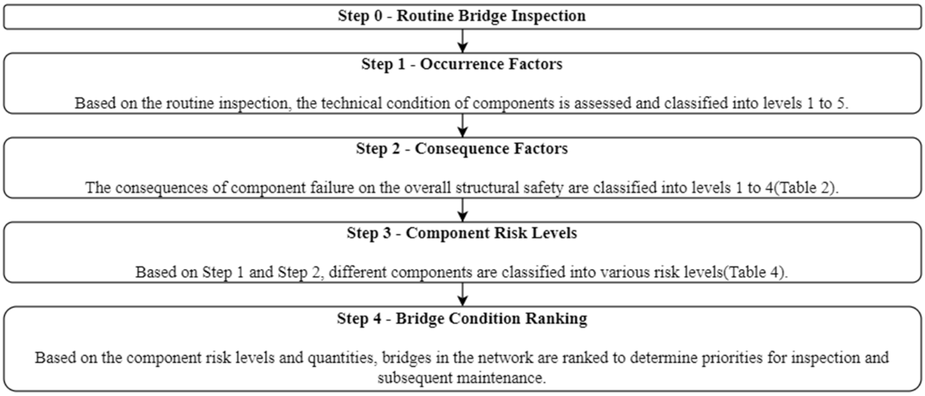

Fig. 1. Flowchart of the Risk-Based Bridge Condition Assessment Method

4.1 Step 1: Occurrence Factors

The first step involves assessing the deterioration state of each bridge component. This evaluation primarily relies on periodic inspection results, with components classified into five levels according to their technical condition.

4.2 Step 2: Consequence Factors

In the Risk-Based Inspection (RBI) process, the second factor to be assessed is the risk level of components, which involves classifying the potential consequences of failure under the assumption that a particular damage mode leads to the failure of the component in question. The objective of this assessment is to measure and differentiate the consequences of component failure in order to determine the importance of each component and prioritize inspection needs. The consequences of component failure are categorized into four levels based on their potential impact on the overall safety of the structure (see Table 2). The consequence factor table for the four levels of components (refer to Table 3) provides general recommendations for component risk levels, which can be appropriately adjusted based on the specific conditions of the bridge.

Table 2. CFs for RBI

level	Category	Description
1	Low	Minimal impact on usability, no impact on safety
2	Medium	Moderate impact on usability, minor impact on safety
3	High	Primarily impacts usability, moderate impact on safety
4	severe	Significant impact on both safety and usability

Table 3. Consequence Factors Related to Structural Components

Component	Ofs	Component	Ofs
Superstructure	4	Superstructure General	3
Bearing	3	Wing Wall	2
Conical Slope	2	Pier	3
Abutment	2	Foundation	2
Riverbed	1	Regulating Structure	1
Bridge Deck Pavement	2	Expansion Joint	2
Sidewalk	1	Parapet	2
Drainage System	1	Lighting Sign	1

4.3 Step 3: Component Risk Level

The third step involves evaluating the risk level of each component by combining the occurrence factors and consequence factors mentioned above. This combination implicitly follows risk analysis principles, with the risk assessment formula expressed as:

Risk = Occurrence Factor × Consequence Factor

Based on this risk analysis, each bridge component is assigned a condition value ranging from I to V, as shown in Table 4. In this framework, the component's risk value increases with the rise in its degradation status, i.e., as the occurrence factor increases, the probability of failure also grows. Similarly, as the consequence factor increases, the component's risk becomes more significant since higher consequences indicate more severe impacts of potential failures. This evaluation reflects the risk posed to the overall structural safety and functionality due to the component's degradation. The component risk values derived from this process will be used in the next step to prioritize the maintenance and inspection of bridges across the entire network.

Table 4. Risk Level Matrix

<table>
<tr><td rowspan="5">Occurrence factor</td><td>5</td><td>III</td><td>II</td><td>I</td><td>I</td></tr>
<tr><td>4</td><td>IV</td><td>III</td><td>II</td><td>I</td></tr>
<tr><td>3</td><td>V</td><td>IV</td><td>III</td><td>II</td></tr>
<tr><td>2</td><td>V</td><td>V</td><td>IV</td><td>III</td></tr>
<tr><td>1</td><td>V</td><td>V</td><td>V</td><td>V</td></tr>
<tr><td colspan="2" rowspan="2"></td><td>1</td><td>2</td><td>3</td><td>4</td></tr>
<tr><td colspan="4">Consequence factor</td></tr>
</table>

4.4 Step 4: Bridge Condition Ranking

The final step involves ranking the numerous bridges within the network based on their component risk values. This ranking depends on both the highest risk value among the components of each bridge and the quantity of components with different risk levels. Bridges with higher individual component risk values and a larger number of high-risk components are given higher priority, indicating greater importance for inspection and maintenance. For bridges with high rankings and components exhibiting significant risks, repair, maintenance, or reinforcement should be carried out, with emergency measures implemented if necessary. Additionally, the inspection intervals for these bridges may be shortened. Conversely, for lower-ranked bridges with low component risk values, routine maintenance or preventive measures can be applied to prevent further degradation of structural components. At the same time, the inspection intervals for these bridges can be appropriately extended.

This method integrates the results of regular inspections with risk analysis to prioritize bridges across the entire network, thereby optimizing the allocation of maintenance and inspection resources.

5 Case Study

5.1 Overview of the Road Network

In this section, a representative sample of bridges from a total of 1,022 along a specific highway is analyzed. During the regular inspections conducted in 2023, 113 single-span bridges were classified as Grade 1 in technical condition, accounting for 11% of the total; 886 single-span bridges were classified as Grade 2, representing 87% of the total; and 22 single-span bridges were classified as Grade 3, making up 2% of the total. Detailed statistical results of the inspections are presented in Table 5.

Table 5. Statistical Results of Regular Bridge Inspections (Unit: Number of Bridges)

No.	Inspection Results								
	Category		Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total	Bridge with Grade 3 or 4
1	Mainline Bridges	Large Bridges	5	58	0	0	0	63	61
2		Medium Bridges	11	104	0	0	0	115	111
3		Small bridge	88	594	22	0	0	704	630
4	Ramp Bridges		5	5	0	0	0	10	8
5	Overpasses		4	125	1	0	0	130	130
Total			113	886	23	0	0	1022	940

The bridges along this route are primarily reinforced concrete beam bridges constructed between 1995 and 2005, featuring typical structural types such as simple and continuous beams. Most of these bridges have medium to small spans, typically not exceeding 60 meters in length. Given that these bridges were built two to three decades ago, the majority fall into the Grade 2 category with components classified as Grades 3 and 4, thereby representing typical bridge infrastructure in China.

The objective of this study is to apply a risk-based analysis to scientifically prioritize the maintenance of the bridges in this network. Since the inspection results show that the majority of the bridges are classified as Grade 2, and the current standards recommend either corrective or preventive maintenance for Grade 2 bridges, the focus of this research is how to allocate inspection and maintenance resources efficiently. The goal is to ensure that these resources are directed toward the bridges with the highest need. The following section will provide a detailed explanation of the implementation process for prioritizing bridge maintenance.

5.2 Bridge Component Risk Assessment

In this section, a representative bridge is selected for component risk assessment based on the results of the regular inspections conducted in 2023. The bridge is a prestressed reinforced concrete prefabricated beam bridge, with a total length of 51.4 meters, completed and opened to traffic in 1999. Due to the impacts of the natural environment, load variations, and material aging over its long service life, some components of the bridge have exhibited varying degrees of performance deterioration and defects, resulting in a technical condition rating of Grade 3 for the current year. The table 6 below presents the assessment of the bridge components using a risk-based approach, incorporating the latest results from the 2023 regular inspection.

Table 6. Risk Assessment of this Bridge Components

Component	OFs	CFs	Risk Level	Component	OFs	CFs	Risk Level
Superstructure	4	4	I	Superstructure General	1	3	V
Bearing	1	3	V	Wing Wall	1	2	V
Conical Slope	2	2	IV	Pier	2	3	IV
Abutment	4	2	III	Foundation	1	2	V
Riverbed	/	1	/	Regulating Structure	/	1	/
Bridge Deck Pavement	3	2	IV	Expansion Joint	3	2	IV
Sidewalk	/	1	/	Parapet	4	2	III
Drainage System	/	1	/	Lighting Sign	1	1	V

5.3 Priority Ranking of Selected Bridges

After selecting ten Category Grade 2 bridges within the road network for risk analysis(Table 7), we determined the risk levels for each component and subsequently prioritized all the bridges based on these levels, focusing first on those with poorer technical conditions. For example, bridges rated as Grade 3 are prioritized over those rated as Grade 2 to address significant hazards. Bridges with the same technical condition rating are sorted by the highest risk level of their components, with those at Risk Level II taking precedence over those at Risk Level III, ensuring that bridges with critical higher risks receive maintenance resources first. When the highest risk levels are the same, we compare the number of components at that risk level, prioritizing bridges with a greater number of such components to fully account for the overall risk.

Table 8 compares the results of prioritization based on technical condition scores and component risk rankings, revealing certain discrepancies that reflect different assessment emphases. The technical condition score primarily relies on the surface damage of the bridge, making it more suitable for evaluating the current physical state of the bridge. In contrast, risk analysis focuses on the potential future damage risks of bridge components, taking into account both the risk levels and the number of high-risk components. This difference allows for the prioritization of bridges with significant hazards in the risk ranking. For example, Bridge 1 ranks sixth in terms of technical condition score but is ranked first in the risk assessment, indicating that risk analysis can expose potential issues in advance and reduce the likelihood of unexpected risks during future operations. This approach to prioritization enhances the rationality and specificity of the allocation of inspection and maintenance resources, directing maintenance efforts toward the bridges that require them most.

Table 7. Ranking of 10 Category 2 Bridges by Component Risk Level

	Bridge 1	Bridge 2	Bridge 3	Bridge 4	Bridge 5	Bridge 6	Bridge 7	Bridge 8	Bridge 9	Bridge 10
Superstructure	II	II	II	II	III	III	III	III	III	III
Superstructure General	IV	III	IV	IV	III	III	IV	IV	V	V
Bearing	V	IV	V	V	IV	IV	III	V	V	V
Wing Wall	V	V	V	/	V	V	/	/	/	/
Conical Slope	IV	V	V	V	V	IV	V	V	V	V
Pier	III	IV	V	V	V	IV	V	IV	IV	IV
Abutment	IV	V	IV	IV	V	IV	IV	V	V	IV
Foundation	V	V	V	V	V	V	V	V	V	V
Riverbed	V	V	/	/	/	V	V	/	/	/
Regulating Structure	/	/	/	/	/	/	/	/	/	/
Bridge Deck Pavement	IV	V	IV	V	V	V	V	IV	IV	IV
Expansion Joint	IV	IV	IV	IV	IV	IV	IV	IV	IV	IV
Sidewalk	/	/	/	/	/	/	/	/	/	/
Parapet	V	V	V	V	IV	V	V	IV	V	V
Drainage System	V	V	/	/	/	V	V	/	/	/
Lighting Sign	V	V	V	V	V	V	V	V	V	V

Note: "/" indicates that the bridge does not have the corresponding component.

Compared to technical condition scoring, risk analysis places greater emphasis on the status of critical components. It not only examines the highest risk level of bridge components but also evaluates the number of high-risk components. For instance, Bridge 10 ranks fifth in technical condition scoring but drops to tenth in the risk ranking, indicating that its critical components have lower risks and thus have a limited impact on the overall priority. Through this detailed component-level assessment, risk analysis can more accurately identify bridges that require focused attention, enhancing management precision. Additionally, risk analysis is forward-looking and effectively supports preventive maintenance, helping to avoid sudden failures caused by the accumulation of hazards. For example, Bridge 1, although having a relatively good technical condition rating, has a larger number of high-risk components. As a result, it ranks first in the risk assessment, indicating the need for early preventive maintenance.

Risk analysis offers significant advantages in bridge management. Unlike technical condition scoring, it focuses on identifying potential risks, precise resource allocation, and monitoring critical components, while also supporting preventive maintenance to effectively reduce the likelihood of future incidents. Therefore, in practical bridge management, combining risk analysis with technical condition scoring enables an understanding of the current state of bridges and allows for proactive maintenance in high-risk areas, ensuring their safe and stable operation.

Table 8. Comparison of Rankings Based on Condition Scores and Component Risk Levels

Name	Condition Score	Score-Based Ranking	Risk-Based Ranking	Name	Condition Score	Score-Based Ranking	Risk-Based Ranking
Bridge 1	87.24	6	1	Bridge 2	84.44	3	2
Bridge 3	88.66	8	3	Bridge 4	82.83	2	4
Bridge 5	84.44	3	5	Bridge 6	81.97	1	6
Bridge 7	88.81	10	7	Bridge 8	88.67	9	8
Bridge 9	88.46	7	9	Bridge 10	85.31	5	10

6 Conclusions

This paper proposes a risk-based framework that combines periodic inspections and risk analysis to rank the bridges along the route, optimizing resource allocation and reducing unnecessary maintenance on low-risk bridges, thereby achieving significant cost savings. Simultaneously, by early identification and management of high-risk components, preventive measures can be taken before deterioration escalates, thus reducing costly repair expenses. This approach minimizes investment in low-risk bridges, leading to lower labor and management costs while maintaining the overall condition of the bridges at a satisfactory level. The following are the limitations of the proposed risk-based framework and specific considerations for its implementation:

1.The risk-based bridge inspection method primarily targets typical highway bridges with common design features. Non-typical structures, such as long-span truss bridges, cable-stayed bridges, suspension bridges, and other unique or unusual bridge designs, may need to consider additional factors.

2.By ranking bridges based on risk analysis, inspection resources can be reallocated to those that require the most attention, enhancing resource utilization and ensuring that inspection resources are used efficiently, ultimately improving the safety and reliability of the bridges.

3.The risk-based bridge inspection method involves reallocating inspection resources according to the priority of potential risks for bridges to ensure their safety, rather than merely reducing inspection requirements to save resources.

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