From a Probabilistic Perspective, the Construction of a Prevention Mechanism for Bridge Accidents

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Abstract

This article aims to deeply explore the construction of a bridge accident prevention mechanism from a probabilistic perspective. Firstly, the severity of bridge accidents and the necessity of studying from a probabilistic perspective were expounded. Then, various factors influencing the occurrence of bridge accidents and their probabilistic characteristics were analyzed, including design factors, construction factors, material factors, environmental factors, and usage and maintenance factors, etc. Then, the probability-based bridge accident risk assessment method was elaborated in detail, including steps such as risk identification, probability estimation and risk evaluation. On this basis, targeted strategies for constructing bridge accident prevention mechanisms were proposed, covering aspects such as the design stage, construction stage, usage and maintenance stage, as well as monitoring and management throughout the entire life cycle.

Keywords: Bridge accident; Probability analysis; Preventive mechanism; Risk assessment.

1. Introduction

1.1 Research Background and Significance

Bridges, as a key component of transportation infrastructure, play an indispensable role in promoting economic development and ensuring social life. However, in recent years, the frequent occurrence of bridge accidents has become a problem that cannot be ignored, causing huge losses to people's lives and property, and also drawing widespread attention from all sectors of society. For instance, the collapse of the Morandi Bridge in Italy in 2018 not only claimed dozens of lives but also caused prolonged traffic disruptions, with far-reaching and widespread impacts [1]. These accidents not only reveal the potential problems existing in every link of bridge planning, design, construction, use and maintenance, but also highlight the urgency of establishing a scientific and effective bridge accident prevention mechanism.

Studying the mechanism of bridge accident prevention from the perspective of probability theory not only holds significant theoretical value but also has remarkable practical significance. Probability theory provides us with an effective tool to quantify uncertainty, which can help us assess the possibility of bridge accidents more accurately, thereby taking targeted preventive measures to reduce accident risks and enhance the safety and reliability of Bridges [2].

1.2 Current Research Status at Home and Abroad

Research on bridge accident prevention and risk management abroad started earlier and has formed a relatively complete theoretical system and practical methods. Many developed countries have established strict bridge design norms and safety assessment standards, and have adopted advanced technical means to continuously monitor and maintain Bridges. For instance, through long-term accumulation and analysis of bridge monitoring data, the United States has established a bridge health monitoring system, which can grasp the structural status of Bridges in real time and promptly identify potential safety hazards [3].

In contrast, although domestic research in the field of bridge safety has made certain progress, there is still a certain gap. In recent years, with the continuous expansion of bridge construction scale and the increasingly prominent problem of bridge aging, domestic scholars have gradually strengthened their research on bridge accident prevention and risk management, and carried out a series of research works on bridge structure reliability, risk assessment and monitoring technology, etc. [4] However, there are still some deficiencies in practical application, which need to be further improved and deepened.

2. Probability Analysis of Influencing Factors of Bridge Accidents

2.1 Design Factors

2.1.1 Design Specifications and Standards

Design specifications and standards are important bases for bridge design, and their rationality and scientificity directly affect the safety and reliability of Bridges. There are certain differences in design standards among different countries and regions. The understanding and implementation of the standards by designers will also affect the quality of the design. From a probabilistic perspective, the imperfection or inadequate implementation of design specifications will increase the probability of bridge accidents. For instance, in terms of the design load value, if the growth trend of the actual traffic load is underestimated, it may lead to the damage of the bridge structure due to insufficient bearing capacity during long-term use [5].

2.1.2 Design Methods and Theories

With the continuous development of bridge engineering technology, design methods and theories are also constantly being updated and improved. However, some traditional design methods and theories may have certain limitations and cannot fully consider the load-bearing performance and durability of bridge structures in complex environments. For instance, in seismic design, if the adopted design method fails to accurately simulate the impact of seismic actions on bridge structures, it may lead to severe damage to the bridge during earthquakes [6]. Therefore, the imperfection of design methods and theories will also increase the probability of bridge accidents.

2.2 Construction Factors

2.2.1 Construction Quality

Construction quality is one of the key factors affecting the safety of Bridges. If there are problems such as cutting corners, non-standard construction techniques, and lax quality inspection during the construction process, it will lead to quality defects in the bridge structure, such as insufficient concrete strength, steel bar corrosion, and excessive prestress loss, thereby reducing the load-bearing capacity and durability of the bridge and increasing the probability of accidents. For instance, during the construction of a certain bridge, due to poor quality of concrete pouring, cracks appeared in the beam body. As the bridge was used later, the cracks continued to expand, eventually leading to a bridge collapse accident [7].

2.2.2 Construction Management

The level of construction management directly affects the quality and progress of construction. If construction management is poor, such as unreasonable construction organization, inadequate safety measures, and insufficient training of construction personnel, it is easy to cause chaos at the construction site and increase the risk of safety accidents. For instance, during high-altitude operations on Bridges, if safety protection measures are inadequate, construction workers may fall, which not only affects the construction progress but also may cause damage to the bridge structure [8].

2.3 Material Factors

2.3.1 Material Quality

The quality of materials used in bridge construction is directly related to the structural performance and service life of the bridge. If the quality of materials does not meet the design requirements, such as insufficient strength of steel or poor durability of concrete, it will lead to various diseases of the bridge structure during long-term use, such as corrosion, cracking and deformation, seriously affecting the safety and reliability of the bridge. For instance, a certain bridge collapsed due to the use of substandard steel, which led to fatigue fracture of the steel beams under long-term loading.

2.3.2 Material Aging

Bridge materials may age due to the influence of environmental factors during long-term use, such as carbonation of concrete and rusting of steel bars. Material aging can lead to a decline in the mechanical properties of bridge structures, a reduction in load-bearing capacity, and an increase in the probability of accidents. For instance, as the service life of a bridge increases, the corrosion of the steel bars in the concrete will gradually intensify, resulting in a reduction in the effective cross-sectional area of the steel bars and a decline in the bonding force between the steel bars and the concrete, thereby affecting the overall performance of the bridge structure.

2.4 Environmental Factors

The influence of natural environmental factors on Bridges mainly includes earthquakes, floods, typhoons, freezing, etc. These natural disasters are sudden and unpredictable, which can cause severe damage to bridge structures. For instance, seismic action can cause significant displacement and deformation in bridge structures, and even lead to bridge collapse. Flood impact can erode the foundation of Bridges and reduce their load-bearing capacity. Typhoons can generate strong wind loads, posing a challenge to the wind resistance stability of Bridges [9].

Human environmental factors mainly include traffic loads, surrounding engineering construction, etc. With the continuous increase in traffic flow and the growth of vehicle loads, the load that Bridges bear is also getting larger and larger. Long-term overloading operation will accelerate the damage of bridge structures and increase the probability of accidents. In addition, surrounding construction projects such as foundation pit excavation and underground tunnel construction may have adverse effects on the bridge foundation, leading to problems such as settlement and inclination of the bridge structure.

2.5 Usage and Maintenance Factors

The management of bridge usage encompasses aspects such as traffic control, load limitation, and regular inspection. If the management is poor, such as severe overloading of vehicles, lack of regular inspection and maintenance, etc., it will accelerate the damage of the bridge structure and shorten the service life of the bridge. For instance, in some regions, in pursuit of economic benefits, the supervision over vehicle overloading is lax, resulting in serious damage to Bridges in a short period of time and affecting the safe operation of Bridges.

Regular maintenance and upkeep are important measures to ensure the safe operation of Bridges. If maintenance and upkeep are not timely or adequate, minor defects in bridge structures may gradually develop into major ones, eventually leading to bridge accidents. For instance, if bridge bearings are not maintained and serviced for a long time, problems such as aging and damage will occur, affecting the load-bearing performance of the bridge structure and leading to uneven settlement and deformation of the bridge.

3. Probability-based Risk Assessment Method for Bridge Accidents

3.1 Risk Identification

Risk identification is the first step in bridge accident risk assessment, with the aim of identifying various risk factors that may lead to bridge accidents. Risk identification can be carried out through methods such as literature research, expert investigation, and historical accident analysis. For instance, through the analysis of bridge accident cases both at home and abroad, common factors affecting bridge safety have been summarized, such as design flaws, construction quality issues, material aging, and natural disasters. At the same time, in light of the specific circumstances of the bridge, identify the special risk factors that the bridge may face.

3.2 Probability Estimation

Probability estimation is the process of determining the likelihood of each risk factor occurring. For some risk factors that can be obtained through historical data statistics, statistical methods can be adopted for probability estimation. For instance, based on the damage of Bridges in a certain area under seismic action, the probability of earthquakes of different intensities occurring and the probability of Bridges being damaged under earthquakes of different intensities are calculated. For some risk factors lacking historical data, methods such as expert assessment and analytic hierarchy process can be adopted for probability estimation. The expert assessment method involves inviting experts in relevant fields to evaluate the likelihood of risk factors occurring based on their own experience and knowledge. The Analytic Hierarchy Process (AHP) breaks down complex risk issues into multiple levels, determines the relative importance of each factor through pairwise comparisons, and then calculates the probability of each risk factor occurring.

3.3 Risk Assessment

Risk assessment is a comprehensive evaluation of the risk level of bridge accidents based on the results of risk identification and probability estimation. Commonly used risk assessment methods include the risk matrix method and the fuzzy comprehensive evaluation method, etc. The risk matrix method classifies the probability of occurrence of risk factors and the severity of consequences into different levels respectively, and then determines the risk level based on the combination of the two. The fuzzy comprehensive evaluation method utilizes the theory of fuzzy mathematics, taking into account the fuzziness and uncertainty of risk factors, to conduct a comprehensive assessment of the risk of bridge accidents. Through risk assessment, the risk level of bridge accidents can be determined, providing a basis for formulating targeted preventive measures.

4. Strategies for Building a Bridge Accident Prevention Mechanism

4.1 Preventive Strategies in the Design Stage

Constantly revise and improve the design norms and standards for Bridges, fully considering the load-bearing performance and durability requirements of Bridges under different environmental conditions. Strengthen the publicity and training of design standards to enhance the understanding and implementation ability of design personnel regarding the standards. At the same time, designers are encouraged to adopt advanced design methods and theories to enhance the quality and reliability of bridge design.

Establish a strict design review system to conduct multi-level and multi-faceted reviews of bridge design schemes. The review content includes the accuracy of the design calculation book, the rationality of the structural design, and the completeness of the construction measures, etc. Invite experts from relevant fields to participate in the design review to ensure that the design plan complies with the principles of safety, economy and applicability.

4.2 Prevention Strategies During the Construction Phase

Establish and improve the construction quality management system and strengthen the quality control during the construction process. Strictly implement the construction process standards, strengthen the quality inspection of raw materials, components and equipment, and ensure that the construction quality meets the design requirements. Strengthen the training and management of construction personnel, and enhance their quality awareness and operational skills.

Strengthen the management of construction organization, rationally arrange the construction progress and sequence, and ensure the safety and order of the construction process. Establish a complete safety management system and emergency response plan, strengthen safety inspections and supervision at the construction site, and promptly identify and eliminate potential safety hazards. Strengthen communication and coordination with relevant departments, solve problems arising during the construction process, and create a favorable external environment for the construction.

4.3 Use Preventive Strategies During the Maintenance Phase

Strengthen traffic control over the use of Bridges and strictly limit the behavior of overloading vehicles. Set up obvious traffic signs and load limit signs to guide vehicles to pass through reasonably. Regularly conduct load tests and structural inspections on Bridges to understand their actual load-bearing capacity and structural conditions, providing a scientific basis for the use and management of Bridges.

Formulate a detailed bridge maintenance and care plan and carry out regular maintenance and care of the Bridges. This includes the cleaning, anti-corrosion and reinforcement of bridge structures, as well as the timely replacement of damaged components and equipment. Strengthen the maintenance and upkeep of key parts such as bridge bearings and expansion joints to ensure their normal operation. At the same time, establish a bridge maintenance and upkeep file to record the maintenance and upkeep conditions as well as changes in the structural state of the Bridges, providing a guarantee for the long-term safe operation of the Bridges.

4.4 Full Life Cycle Monitoring and Management Strategies

By leveraging modern sensor technology, communication technology and computer technology, a bridge health monitoring system is established to monitor the structural condition and environmental parameters of Bridges in real time. The monitoring content includes the stress, strain, displacement, vibration, etc. of the bridge, as well as the environmental temperature, humidity, wind speed, etc. Through the analysis and processing of monitoring data, abnormal changes in the bridge structure can be detected in a timely manner, providing a basis for the safety assessment and maintenance decision-making of the bridge.

Adopting the concept of full life cycle management, the entire process of Bridges, from planning, design, construction, use to demolition, is managed. Establish a bridge full life cycle information management system to integrate information from all stages of the bridge and achieve information sharing and collaborative management. Through the analysis of the cost and benefits throughout the entire life cycle of Bridges, the design, construction and maintenance plans of Bridges are optimized to enhance their comprehensive benefits.

5. Conclusion

This article conducts an in-depth study on the construction of a bridge accident prevention mechanism from a probabilistic perspective. The occurrence of bridge accidents is the result of the combined effect of multiple factors. Design factors, construction factors, material factors, environmental factors, and usage and maintenance factors all affect the probability of bridge accidents.

The probability-based bridge accident risk assessment method can accurately evaluate the risk level of bridge accidents and provide a scientific basis for formulating targeted preventive measures. To establish a scientific and reasonable bridge accident prevention mechanism, it is necessary to start from aspects such as the design stage, construction stage, use and maintenance stage, as well as the monitoring and management throughout the entire life cycle, and take comprehensive measures to improve the safety and reliability of Bridges.

Although this paper has achieved certain research results in the construction of bridge accident prevention mechanisms, there are still some deficiencies that need to be further improved and deepened in future research. For instance, it is necessary to enhance the research on bridge health monitoring technology, develop more advanced and reliable monitoring equipment and data analysis methods, and achieve real-time and precise monitoring of the structural status of Bridges. Conduct in-depth research on the theories and methods of bridge full life cycle management, establish a more complete bridge full life cycle information management system, and enhance the comprehensive benefits of Bridges. Strengthen policy support and legal guarantees for the prevention mechanism of bridge accidents, and promote the standardization and normalization of bridge safety management. Through continuous research and practice, it is believed that a more scientific and complete bridge accident prevention mechanism can be established, effectively reducing the risk of bridge accidents and ensuring the safety of people's lives and property as well as the safe operation of transportation infrastructure.

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