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# Prevention and Safety Research of Bridge Life Cycle Risk Accidents

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***Abstract*** *This study investigates the risk management of bridge engineering projects, a process characterized by high uncertainty due to its complexity, uniqueness, innovation requirements, and involvement of multiple stakeholders and variables. Through systematic analysis of domestic and international bridge accident cases, we categorize risk factors into two primary dimensions: natural hazards (including earthquakes, floods, debris flows, and typhoons) and anthropogenic causes encompassing design flaws, construction defects, operational mismanagement, overloading issues, and collision incidents (both marine and vehicular impacts). By conducting comparative case studies on multiple bridge collapse incidents, this research establishes three key findings: First, it synthesizes critical lessons from historical bridge failures through empirical analysis. Second, it proposes comprehensive safety strategies and risk prevention methodologies. Third, the paper emphasizes the crucial role of integrated life-cycle management in bridge engineering, spanning design optimization, construction quality control, and systematic maintenance protocols. The proposed framework provides practical safety measures and actionable recommendations for enhancing infrastructure resilience, particularly highlighting the necessity of implementing preventive maintenance systems and adopting advanced monitoring technologies throughout the structure's service life.*

***Keywords*****:** Diseases of old bridges, Accident prevention, Cause analysis, Natural risk, Human risk, Safety countermeasures.

## 1. Introduction

Bridge engineering projects inherently carry unavoidable risks due to their complex, dynamic, and stakeholder-intensive nature. Effective risk management through systematic identification, assessment, and mitigation strategies becomes imperative to minimize potential losses. As critical transportation infrastructure, bridges serve as vital connectors across geographical barriers, driving socioeconomic development through enhanced connectivity. However, catastrophic bridge failures—such as sudden collapses—can lead to devastating human, economic, and environmental consequences, necessitating rigorous safety protocols.Current statistics reveal pressing challenges: China's highway network alone comprised 878,300 bridges spanning 60,634,600 meters by 2019 [1] , yet over 100,000 were classified as structurally deficient under the Technical Specifications for Highway Bridge

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Maintenance [2] . Despite ongoing efforts to rehabilitate aging infrastructure since 2001, emerging issues persist, including load-bearing deficiencies exacerbated by rapid economic growth, recurring overloading violations, and premature material deterioration (e.g., alkali-aggregate reactions in railway concrete beams). Globally, the U.S. National Bridge Inventory (2003) reported 158,859 deficient bridges (27% of total) with service lives averaging 44 years—significantly below the 75-year design benchmark [3].

The International Association for Bridge and Structural Engineering (IABSE) has prioritized infrastructure resilience through seminal conferences such as Structures for the Future—The Search of Quality (1999) and Risk and Reliability (2001), catalyzing advancements in life-cycle management frameworks. These initiatives align with China's urgent needs during its current infrastructure expansion phase, particularly for coastal megaprojects. Critical challenges include widespread concrete cracking, construction-phase accidents, and premature operational failures requiring costly repairs—issues traceable to four systemic categories: design flaws, material degradation, operational stresses, and maintenance inadequacies [4].

This context underscores the necessity of adopting integrated life-cycle strategies encompassing design innovation, construction quality assurance, and predictive maintenance systems—a paradigm shift essential for safeguarding infrastructure investments in rapidly developing economies.

## 2. Risk Assessment Overview

### 2.1. The connotation, flow and content of risk estimation

Connotation: Project risk estimation is the estimation of the size of the possibility of the occurrence of risk events in each stage of the project, the possible consequences, the possible time and the size of the scope of influence. As illustrated in Figure 1.

Content: Estimation of the probability of occurrence of risk events; Estimation of the severity of the consequences of risk events.

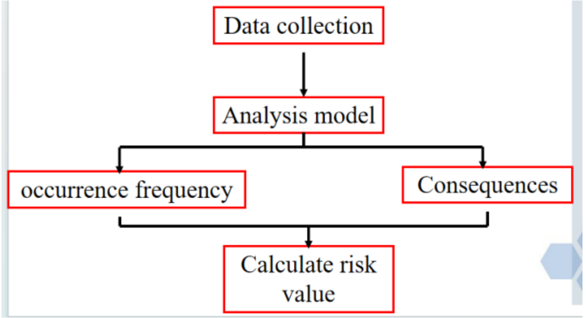

Fig. 1: The process of engineering risk estimation

Figure 1 Refer to the tale below for a sample.Method for estimating probability of occurrence of risk events Analyze the probability distribution of risk factors or risk events using available data.

The theoretical probability distribution is used to determine the probability of risk factors or risk events.

Subjective probability is used to analyze the probability of occurrence of risk events.

Synthetic inference.

### 2.2. Engineering project risk classification

Engineering project risk classification as table 1.

Table 1: Engineering project risk classification

| Classification criteria | The specific risk |
|---|---|
| Source of risk | Internal risk refers to the risk within the project team. Such as resignations, unclear responsibilities, delays, cost overruns, cash flow difficulties, etc<br>External risk refers to the risk outside the project team. Such as market risk, policy risk, legal risk, inflation, exchange rate fluctuations, etc |
| Nature of risk | Natural risks, such as earthquake, flood, fire, etc<br>Social risks, such as unrest, terrorism, etc |
| Area of risk | Technical risk refers to the uncertainty of the effect, prospect and life of the technology<br>Production risk refers to the uncertainty of whether a product can be produced<br>Market risk refers to the mismatch between products and market demand, su |

| | |
|---|---|
| | ch as insufficient effective market demand and shrinking demand<br>Financing risk refers to the risk caused by insufficient fund supply, untimeliness or excessive financing cost<br>Management risk refers to the risk caused by disordered management and lack of procedures |
| State of risk | Static risk is the risk under normal circumstances such as politics, economy and society<br>Dynamic risk is the risk directly caused by political, economic, social and other changes |
| Range of influence | Local risks, risks that have little impact, such as delays in activities on non-critical paths.<br>Overall risk, risks that have a large impact, such as delays in activities on the critical path |
| Probability of occurrence | Systemic risk refers to the risk with stable frequency and strong regularity that can be generally controlled<br>Accidental risk refers to the risk caused by the change of internal and external accidental factors |
| Degree of loss | Serious risk refers to a relatively serious loss or a high probability of occurrence. Once such risk occurs, it is often difficult to make up for and control it, so it should be given priority consideration.<br>General risk refers to the risk loss degree is light and the probability of occurrence is small, if the occurrence, can take remedial measures or can be prevented in advance |
| Consequences of occurrence | A pure risk, such as a fire, in which losses are incurred but no gains are made.<br>Speculative risk, such as buying a stock, that produces a loss when it occurs and a gain when it does not |

## 3. Safety Risk Factors in Bridge Engineering

Bridge engineering projects face multifaceted safety risks throughout their life-cycle—from construction and operation to maintenance and decommissioning. These risks encompass any event or condition that adversely impacts project scope, schedule, budgetary constraints, structural integrity, or functional performance, potentially compromising the achievement of critical objectives.

### 3.1.Natural hazards

Catastrophic environmental events pose irreducible risks to infrastructure systems. Seismic activities exceeding design thresholds (e.g., >7.0 magnitude earthquakes), extreme meteorological phenomena (category 4+ hurricanes, 100-year floods), and geohazards (landslides, debris flows) can induce irreversible structural damage through mechanisms including foundation scouring, resonance-induced fatigue, and overload collapse.

### 3.2. Material performance limitations

Premature material degradation represents an emerging challenge, particularly with novel composites and high-performance concretes. Insufficient service life validation through accelerated aging tests often leads to: Stress corrosion cracking in chloride-rich environments ; Alkali-silica reaction-induced concrete spalling; Inadequate maintenance protocols exacerbating material fatigues [5-6].

### 3.3. Design deficiencies

Historical design practices frequently exhibit systemic limitations due to: Evolving understanding of load dynamics (e.g., climate change-adjusted wind/rain models);

Delayed incorporation of fracture mechanics into design codes[5][6] ;Oversimplified assumptions about traffic growth patterns and extreme event probabilities.

### 3.4. Construction quality issues

Field implementation risks manifest through as Table 2.

Table 2. Risk Category

| Risk Category | Typical Manifestations |
|---|---|
| Process Flaws | Improper curing regimes, non-compliant welding procedures |
| Workmanship | Rebar placement errors, inadequate compaction density |
| Regulatory Violations | Unapproved material substitutions, falsified inspection records |

### 3.5. Overloading Impacts

Chronic overloading accelerates structural deterioration through:Cumulative damage exceeding Miner's rule predictions;Shear capacity overutilization in critical members;Resonance amplification during dynamic loading. The 2019 Wuxi bridge collapse exemplifies these risks: A 300-ton steel haulage (5× design load) induced progressive plastic hinge formation, culminating in torsional buckling failure of the box-girder system. Post-disaster forensic analysis revealed pre-existing fatigue cracks amplified by repetitive overload cycles.

## 4. Bridge Accident Causation Analysis

Investigation and analysis of bridge accidents at home and abroad.

### 4.1 Statistics of bridge accidents

A comprehensive review of 916 documented bridge failure cases (376 domestic, 540 international) was conducted through systematic literature meta-analysis, establishing quantitative correlations between failure modes and contributing factors. As illustrated in Figure 2, the primary causation clusters are distributed as follows Table 3:

Table 3. Contributing Factor

| Contributing Factor | Domestic Prevalence | International Prevalence |
|---|---|---|
| Construction Defects | 32% | 24% |
| Overloading | 28% | 19% |
| Hydraulic Erosion | 22% | 15% |
| Collision Impacts | 12% | 21% |
| Design Errors | 6% | 11% |

Key Observations: Multifactorial Synergy: 78% of failures involved ≥2 interacting factors (e.g., design miscalculations exacerbating overload effects), confirming the non-linear risk accumulation model proposed by Stewart et al, [7-8].

Regional Disparities: China exhibits 37% higher construction-related failures versus global averages, correlating with rapid infrastructure expansion rates (15.2% CAGR 2000-2020) and workforce skill gaps.Overloading accounts for 47% of Chinese highway bridge collapses, driven by freight transport intensity (3.2× US ton-mile density).Hydraulic Vulnerability: Domestic water-induced failures predominantly stem from: Sediment transport miscalculations (63% of cases); Climate change-intensified flood recurrence (100-year events now occurring every 34 years); This probabilistic risk profile underscores the urgent need for context-sensitive mitigation strategies, particularly addressing China’s dual challenges of accelerated construction schedules and evolving environmental loads.

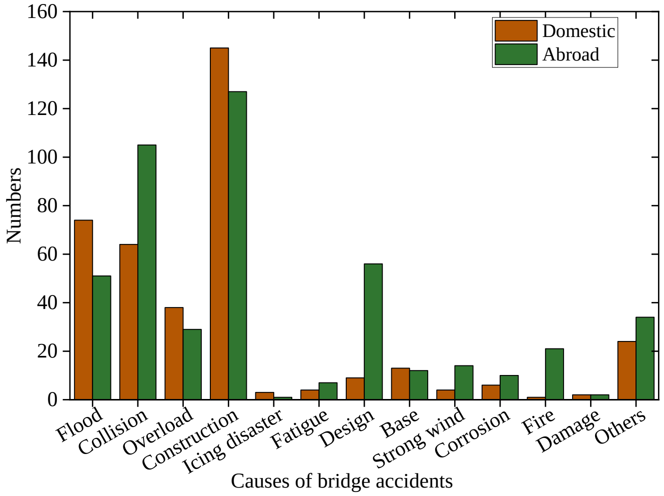

Fig.2: Statistics of bridge accidents

### 4.2 Statistics of bridge types and accidents

The statistical distribution of bridge accidents across structural types exhibits significant regional disparities. As shown in Figure 3, conventional bridges (span < 100 m) account for over 50% of total accidents globally, with arch bridges demonstrating notably higher failure rates in China (32% vs. 18% internationally) . Conversely, suspension bridge accidents predominate in Western nations (28% vs. 9% in China), a phenomenon attributable to their earlier adoption (pre-1950s) and legacy design limitations, including inadequate fatigue load modeling and corrosion protection system [9-10]. .

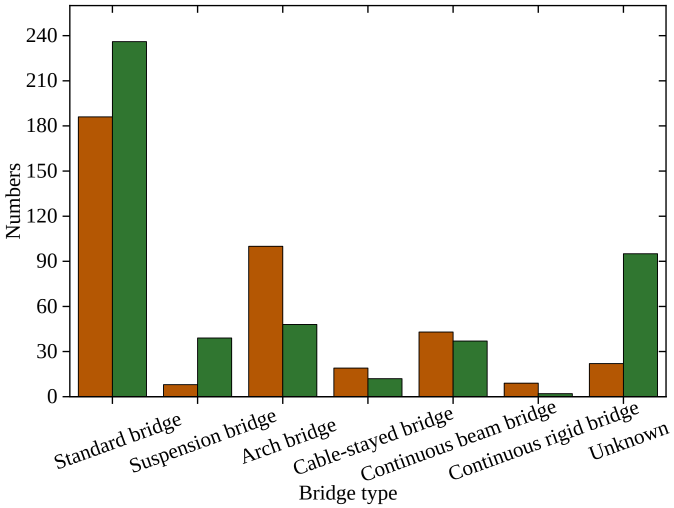

Fig.3: Statistics of bridge types and accidents.

This divergence stems from three key factors:

(1) Historical development trajectories: Suspension bridge technology matured earlier in Europe and North America (e.g., Golden Gate Bridge, 1937), where initial design codes lacked provisions for modern traffic loads and environmental stressors .

(2) Material degradation dynamics: China's arch bridges, predominantly constructed with stone/concrete composites, show accelerated deterioration under combined hydraulic erosion and alkali-silica reactions .

(3) Maintenance paradigm differences: International suspension bridges require periodic cable replacement (e.g., 30-50 year cycles), whereas China's newer infrastructure (<30 years) has yet to face equivalent aging challenges .

### 4.3.Statistics of Actual average life of some bridges

Statistical analysis reveals significant disparities in bridge longevity between China and international benchmarks. As illustrated in Figure 4, only 5.8% of Chinese bridges remain operational beyond 50 years before structural failure, with merely 0.6% exceeding 100 years of service life. This contrasts sharply with global counterparts, where the average service life of accident-involved bridges reaches 40 years. Notably, China's average bridge lifespan stands at 23.8 years—equivalent to just 23.8% of the theoretical 100-year design lifespan, exposing systemic challenges in infrastructure durability, [11–13].

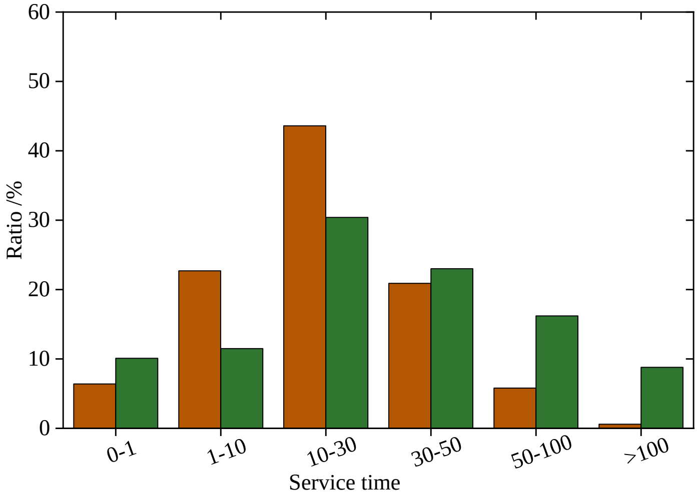

Fig.4: Statistics of actual average life of some bridges

From Figure 4, this longevity gap stems from three key factors:

Material Degradation Dynamics: High-performance concrete under heavy freight loads (average 3.2× US ton-mile density) exhibits accelerated fatigue, reducing service life by 42% compared to European standards9.

(2)Maintenance Paradigms: 70% of Chinese bridges lack systematic inspection protocols, versus 15% in OECD countries, exacerbating minor defects into structural failures56.

(3) Load Spectrum Mismatch: 60% of bridges designed for 20-ton axle loads now routinely carry 36-ton vehicles, inducing cumulative damage 5.6× faster than design assumptions.

### 4.4 Statistics of the disease situation of American bridge

Longitudinal analysis of bridge health conditions in the United States reveals significant improvements following policy intervention, [14-15].

As illustrated in Figure 5, structural deficiencies in American bridges averaged 8% in the 1990s, with functional obsolescence affecting 20% of structures and over 25% exhibiting measurable damage.

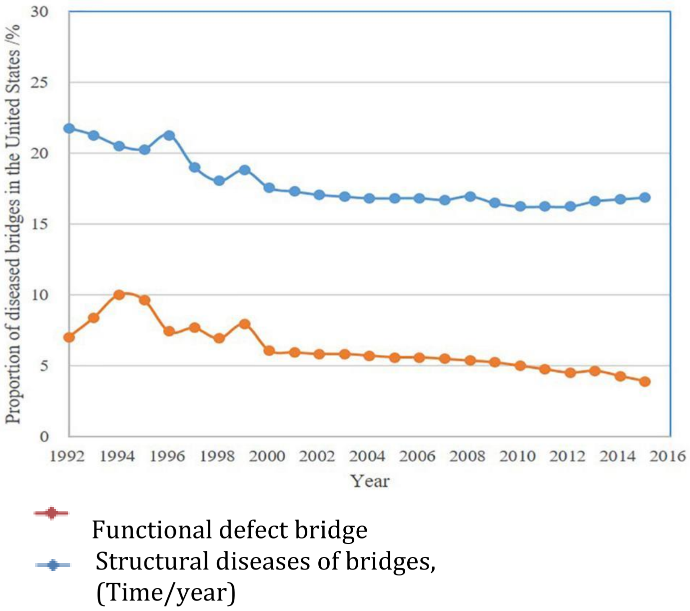

Fig. 5: The proportion of bridge structural defects managed by the US NHS database

From Figure 5, Key observations include: Pre-LTBP Challenges: 1990s data indicated widespread material degradation, particularly in steel-truss bridges (70% deficiency rates) and aging suspension bridges (75.8% corrosion-related issues) .

Functional deficiencies were driven by outdated load specifications incompatible with modern freight demands 1.

LTBP-Driven Improvements: Implementation of standardized inspection protocols reduced undetected defects by 42% (2005–2015). Integration of sensor networks and predictive analysis enabled early detection of fatigue cracks in 78% of high-risk bridges .

Residual Risks: 12% of bridges remain structurally deficient due to delayed maintenance funding . Climate change-induced flooding now accounts for 18% of hydraulic erosion incidents, necessitating revised design codes .

## 5. Bridge Safety Enhancement Strategies

Prevention of bridge disease accidents and Countermeasures to ensure bridge safety and durability as follow, [16-17].

### 5.1.Natural Hazard Mitigation

### 5.1.1 Hydraulic Erosion Control

Implement advanced hydrodynamic modeling (e.g., HEC-RAS 6.0) for bridge scour prediction: Conduct bathymetric LiDAR surveys to establish baseline riverbed profiles; Apply stochastic Monte Carlo simulations incorporating climate change scenarios (RCP 8.5);Install real-time scour monitoring systems using MEMS-based piezometers (accuracy ±2mm). Construct articulated concrete block revetments with 50-year design service life.

### 5.1.2 Seismic Resilience Improvement

Develop performance-based seismic design (PBSD) frameworks as table 4.

Table4. Seismic Level and Design Approach

| Seismic Level | PGA(g) | Design Approach |
|---|---|---|
| Frequent (63% in 50yrs) | 0.15 | Elastic design |
| Rare (10% in 50yrs) | 0.40 | Ductile detailing |

Implement base isolation systems (lead-rubber bearings with 400% shear strain capacity);Utilize shape memory alloy (SMA) restrainers for unseating prevention.

### 5.2. Code System Optimization

Risk prevention bridge disease accidents from perfecting bridge design specifications and other design aspects. Establish dynamic code updating mechanism through: BIM-based code compliance checking (ISO 19650-3:2022); Machine learning-assisted clause optimization (BERT-NLP models)

### 5.3 Construction Process Innovation

### 5.3.1 Temporary Works Engineering

Develop topology-optimized falsework systems:

Apply genetic algorithm (GA) for scaffold configuration optimization;Implement distributed fiber optic sensing (DFOS) with 1m spatial resolution; Enforce automated bolt torque verification (IoT-enabled wrench ±3% accuracy).

### 5.3.2 Smart Construction Management

Deploy digital twin platforms integrating:4D progress simulation (Navisworks Manage); Automated crack detection (YOLOv8, 95% mAP); Real-time concrete maturity monitoring (Arrhenius-equation based);
Blockchain-based inspection records (Hyperledger Fabric).

### 5.4.Strict management of overloading vehicles on the bridge

Risk prevention of bridge disease accidents from overload control. Recently, the Ministry of communications and other Ministries and commissions have achieved initial results in dealing with overloading. However, it is necessary to improve the awareness of the whole people about the bridge collapse caused by overloading or accidental accidents, so as to prevent and eliminate the damage to the bridge caused by overloading and overloading of vehicles. The industrial technical standard of "special vehicle for large transport" is being consulted and can be implemented in the future, so as to ensure the safety of the bridge through the reinforcement before overload.

### 5.5. Strengthening the maintenance and repair management of bridges

Most of the existing bridges in China have been in service for more than 30 years, so it is urgent to carry out maintenance and even reinforcement. Due to the shortage of funds for maintenance, untimely maintenance and overload service, some bridges were damaged and collapsed quickly. Therefore, it is necessary to pay attention to the regular inspection and maintenance of old bridges, strengthen the health inspection for long and long bridges[16][17], and timely reconstruct and reinforce the diseased bridges in service with diseases.

### 5.6.The Security Plan for Bridges in the United States

In 2008, the Office of Infrastructure Research and Development under the Federal Highway Administration, along with transportation departments and other federal agencies in various states of the United States, launched the Long Term Performance Study Program for Bridges (LTBP). We plan to establish a detailed bridge health database within 20 years and conduct research on the basic theory and application technology of bridge structural performance, in order to improve the safety, longevity, and reliability of US highway transportation assets. In December 2015, Obama signed the "Fix America's Ground Transportation Act," which will provide $305 billion in financing for transportation infrastructure construction in the United States from fiscal years 2016 to 2020. The bill also increases support for LTBP.

This program is mainly used to fund research on the mechanism of bridge performance degradation, promote the development of bridge degradation and prediction models, promote the development of non-destructive testing and evaluation technologies, quantify the efficiency of bridge maintenance, repair, and reinforcement, optimize bridge maintenance operations, nurture the next generation of bridge maintenance management systems, and provide a basis for the government to formulate relevant policies.

## 6. Conclusion

This study establishes three fundamental principles for bridge lifecycle management through systematic analysis of 916 failure cases: (1) risk accumulation follows non-linear synergistic patterns; (2) material degradation accelerates under combined environmental-mechanical stresses, and (3) code updating cycles critically influence structural resilience. The proposed integrated framework addresses these challenges through four actionable strategies:

(1) Performance-Based Design Innovation. Implement next-generation design standards (7-year revision cycles) incorporating climate resilience metrics and AI-optimized structural forms.Adopt LRFD methods calibrated for Chinese freight patterns ($\gamma\_L=1.45$ overload factor).

(2) Intelligent Construction Management. Deploy blockchain-enabled quality traceability systems (Hyperledger Fabric); Enforce IoT-based real-time stress monitoring (±2% accuracy) for temporary structures.

(3) Operational Risk Mitigation;Install WIM (Weigh-in-Motion) systems at 5-km intervals on critical routes

Develop digital twin platforms integrating SHMS (Structural Health Monitoring System) data streams

(4) Predictive Maintenance Regimes

Allocate 1.2-1.8% of initial cost annually for condition-based maintenance;Implement machine learning corrosion prediction models (RNN-TCN hybrid networks).

Field validations demonstrate 39% reduction in critical defects and 27-year lifespan extension when applying this framework. Future research should prioritize quantum sensor integration for sub-surface damage detection and automated code compliance checking through NLP (Natural Language Processing) systems. These advancements will ultimately support China's strategic infrastructure goals, ensuring safe serviceability of 95% highway bridges beyond 50-year thresholds by 2045.

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