Integrating Forensic Investigation with Risk Assessment for Flyover Bridges: A Case Study

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**Abstract.** The integration of forensic investigations and risk assessments is vital for the practical application of risk management in the construction industry, particularly in the assessment of existing structures like flyover bridges. Despite its importance, there is a noticeable gap in connecting forensic methods and traditional risk assessment frameworks. This study aims to bridge this gap by evaluating a flyover bridge through both qualitative and quantitative methods, utilizing a risk matrix and the analytical hierarchy process (AHP). Risks are identified based on Indian standards, IRM standards, and historical data. The findings indicate that while the Risk Matrix identifies key risks such as land acquisition and financial concerns, AHP provides a more detailed prioritization, emphasizing operational and accessibility risks. Ultimately, operational risk, linked to onsite root causes through forensic investigation, is the top priority. The results underscore the importance of comprehensive forensic analysis in enhancing risk assessment, leading to more effective resource allocation and improved structural safety. This study highlights the critical role of linking forensic investigations with risk assessment and provides an integrated risk assessment framework for better-informed decision-making in industry practices.

**Keywords:** Forensic investigation; Risk assessment; Flyover bridge; Analytical Hierarchy Process (AHP); Risk Matrix; Decision-making.

1. Introduction

Risk assessment is a crucial process in the successful execution of construction projects, particularly in the conditional assessment of existing structures. This involves identifying, analyzing, and prioritizing potential risks that could impact the project’s outcomes. Effective risk management provides a framework for making informed decisions, improving safety, ensuring structural integrity, and optimizing resource allocation. This comprehensive literature survey integrates risk assessment in structural engineering, focusing on condition assessment using forensic structural engineering and structural health monitoring.

Renzi et al. [1] enhanced bridge safety by integrating updated guidelines for risk classification, management, and seismic assessment into Italian regulations. Cutrone et al. [2] addressed landslide risk assessment in bridge management by refining calculation parameters for the “Overall Attention Class” and suggested integrating innovative techniques into Web GIS platforms. Ting Fu et al. [3] introduced a two-stage risk evaluation model that combines the Likelihood Exposure Consequences method and a Bayesian network for analyzing bridge maintenance risks and guiding targeted prevention measures.

Filizadeh et al. [4] proposed a probabilistic framework for optimizing post-earthquake monitoring strategies for reinforced concrete bridges using Monte Carlo simulations. Wang et al. [5] presented a rapid seismic risk assessment framework for bridges using Unmanned Aerial Vehicles (UAV) aerial photogrammetry and Monte Carlo simulations, highlighting the method’s feasibility and efficiency. Lemos et al. [6] analyzed risk management for two bridges in Lisbon, emphasizing the importance of comprehensive risk management in public-private partnerships. Flenga and Favvata [7] presented a risk-targeted decision model for assessing the seismic performance of RC structures to ensure, structural safety with critical separation gaps.

Guzman-Acevedo et al. [8] developed a risk assessment methodology for bridges by integrating Interferometric Synthetic Aperture Radar (In SAR) time series data with a calibrated finite element (FE) model, effectively identifying low-risk probabilities and validating the InSAR’s potential in structural health monitoring. Quincia et al. [9] evaluated the performance-based earthquake engineering (PBEE) approach for industrial plants and found its robustness and reliability in risk assessments. Renzia et al. [10] examined the implementation of the new Italian Guidelines for risk classification and management of existing bridges within an integrated risk management system, focusing on seismic vulnerability and network performance. They concluded that adopting these guidelines and Safety Management Systems (SMS) significantly enhances the safety and resilience of road networks.

The literature reviewed demonstrates the evolution and integration of advanced risk assessment methodologies in bridge management, emphasizing seismic vulnerability, hydrogeological risks, structural health monitoring, and maintenance strategies. By leveraging the insights from these studies, this study aims to develop a comprehensive risk assessment framework tailored to flyover bridges, specifically utilizing the risk matrix and the Analytical Hierarchy Process (AHP) to ensure enhanced safety and resource optimization.

1. Methodology

The methodology for integrating forensic investigation with risk assessment for assessing the condition of a flyover bridge involves several critical steps, as illustrated in **Fig. 1**.



**Fig. 1.** Methodology flow chart for integrating forensic and risk assessment.

Initially, a thorough structural forensic investigation was conducted to gather detailed information on the bridge’s condition and any past incidents. This phase collects relevant data, such as structural details and maintenance records, which are then used to identify and prioritize risks through the project’s Work Breakdown Structure (WBS). A comprehensive risk assessment is then performed using both qualitative and quantitative approaches. Qualitative assessment employs a Risk Matrix to evaluate risks based on their likelihood and impact, whereas quantitative assessment uses the Analytical Hierarchy Process (AHP). The results of these assessments are compared to identify the most critical risks. These critical risks are documented and evaluated to determine whether they fall within tolerable limits. If intolerable, control measures are recommended to mitigate them. For tolerable risks, recommendations are developed to address potential risks in future evaluation and notable for new similar projects, ensuring that lessons learned are applied to improve risk management practices.

This methodology ensures a comprehensive approach to identifying, evaluating, and mitigating risks, effectively linking forensic investigation with risk assessment to enhance decision-making and improve the safety and integrity of the flyover bridge.

* 1. Qualitative Risk Assessment

Qualitative risk assessment is performed using a risk matrix approach, where identified risks are systematically arranged in a matrix based on their risk ratings. These ratings are derived from the product of likelihood and impact probabilities. Likelihood measures the probability of a risk occurring, while impact probability assesses the potential consequences of the risk on the project if it occurs. The evaluation of risks using this matrix is governed by historical data from forensic investigations, IRM guidelines [11], and Indian standards [12]. This approach ensures a comprehensive risk assessment by integrating both historical evidence and established standards to assess the severity and the probability of each risk event. Dey [13] developed an integrated risk management framework that combines the AHP with risk mapping to address project risks at multiple levels. Applied to a 1500 km oil pipeline project, this framework demonstrates its effectiveness in managing both business and operational risks. AHP is used to select the least risky project, while risk analysis at work packages and activity levels is conducted using risk maps.

* 1. Quantitative Risk Assessment

One of the popular tools of quantitative risk assessment is the Analytical Hierarchy Process. It is a multiple-criteria decision-making approach and, is utilized for quantitative risk assessment by employing pairwise comparisons to evaluate the relative importance of various risks and prioritize them accordingly [14]. In the pairwise comparison matrix, diagonal elements are assigned a value of unity, reflecting that each risk is compared to itself. Thus, each risk holds equal importance. For the upper triangle of the matrix (above the diagonal), each risk in a row is compared to the corresponding risk in the column. Values were assigned based on Saaty’s Scale to represent the relative importance of one risk compared to another, pairwise comparisons. For example, if Land Acquisition (R2) is deemed moderately more critical than Inaccurate Traffic Study (R1), a value of 3 (R2 is thrice more critical than R1) is assigned. Conversely, the lower triangle of the matrix (below the diagonal) contains the reciprocals of the upper triangle values; thus, if R2/R1 is 3, then R1/R2 is 1/3. To derive prioritized risks, the eigenvector is obtained by normalizing the pairwise comparison matrix. This was followed by consistency analysis to ensure that judgments align with risk tolerance limits, thus validating the reliability of the risk prioritization process.

Dey [15] integrated the Analytic Hierarchy Process (AHP) and Decision Tree Analysis (DTA) for project risk management by systematically identifying and quantifying risk factors through AHP, evaluating their impact, and generating alternative responses using decision trees. This combined methodology, applied to a cross-country petroleum pipeline project, demonstrates improved decision-making and risk assessment for large-scale construction projects. Similarly, Aminbakhsh [16] presented a safety risk assessment framework that combines the Cost of Safety (COS) model with AHP, thereby aiding in prioritizing safety risks and budgeting for construction projects. Their framework, applied to a real-life project, enhances decision-making for safety investments despite the challenges of extensive pairwise comparisons. These studies highlight the importance of AHPs in developing effective risk management methodologies, informing and enhancing the present approach of integrating forensic investigations into risk assessment for flyover bridges.

1. Case Study

The case study’s forensic investigation was derived from a previous study by Neridu et al. [17]. The study examines a minor box-type bridge with two 4-meter spans, a height of 4 meters, and a total length of 16 meters. The bridge is supported by a pier wall with a thickness of 300 mm, a deck slab, and a bottom raft with a thickness of 400 mm. The construction utilized M30 grade concrete. This twin culvert bridge was diagnosed based on distress observed at the mid-pier wall. The initial visual inspection revealed active vertical cracks with widths greater than 0.3 mm, indicating structural cracking. Additionally, honeycombs and patchworks were noted, which initially suggested poor construction practices. The visual inspection data were further validated using non-destructive testing and numerical analysis. Based on the results of the Rebound Hammer, UPV, and core sample tests, it was concluded that the current strength of the mid-pier wall showed a 40-45% reduction in the design strength. This reduction was attributed to inadequate material mixing, curing, and consolidation, which led to voids, cracks, and other defects, highlighting the potential use of low-quality materials. Numerical analysis provided evidence that cracks, located under the wheel paths of vehicles, developed due to insufficient strength for the transfer mechanism of wheel-load distributions.

The forensic investigation revealed the need for repair and retrofitting of the mid-pier wall to ensure the bridge’s serviceability. Thus, the present study focuses on risk assessment based on forensic data through the proposed framework (refer to Fig. 1) for recommending critical risks and control measures for future project evaluations and any similar projects, ensuring proper functionality and structural safety.

* 1. Risk Identification

The project work breakdown structure is developed as illustrated in **Fig. 2**, and corresponding risks are identified at each level based on the data acquired from the forensic investigations. The data acquisition follows two major approaches in forensic investigations [18]: the pathology-based approach, in which data are collected and interpreted through current condition assessment [17], and the lifecycle-based approach, in which data are gathered throughout the project life cycle. Risk identification and prioritization are then performed based on the acquired data, adhering to standard guidelines [11,12].



**Fig. 2.** Project work break down structure

* 1. Risk Matrix Approach

The classified sectors and their respective risks were assessed using a risk matrix approach during the pre-construction, construction, and post-construction phases. The likelihood and impact are both scaled to 3 based on the number of identified risks, resulting in a 3 x 3 risk matrix. Risk maps, developed by prioritizing identified risks based on forensic data, are shown in **Fig. 3** to **Fig. 5**. The construction phase includes global sectors; feasibility study and design, tendering, project planning, and scheduling.



**Fig. 3(a).** Risk map for feasibility study and design



**Fig. 3(b).** Risk map for procurement and tendering



**Fig. 3(c).** Risk map for project planning and scheduling

The construction phases encompass various sectors, each posing similar equivalent risks due to the sequential nature of constructing structural elements. Level 1 global risks are identified by considering all associated Level 2 risks as shown in **Fig. 4**. For instance, financial risks include budget overruns, project delays leading to financial losses, changes in market value, and currency fluctuations. Similarly, operational risks encompass health and safety hazards, reinforcement alignment issues, quality control concerns, and labor disputes.



**Fig. 4.** Risk map for the construction phase

The post-construction phase of any project includes the maintenance and monitoring of the structure’s serviceability. Maintenance is primarily conducted through visual inspections using forensic methods. Based on the identified requirements and observed distress, further actions, such as non-destructive testing, numerical analysis, and repair and retrofitting, are undertaken.



**Fig. 5(a).** Risk map for visual inspection



**Fig. 5(b).** Risk map for non-destructive evaluation (NDE)



**Fig. 5(c).** Risk map for numerical analysis twining with NDE results



**Fig. 5(d).** Risk map for repair recommendations

This method simplifies the assessment and provides quick qualitative insights into the risks affecting the project. However, it lacks the capability to quantify the risks, meaning that it cannot provide concrete evidence on whether risks can be tolerable.

* 1. AHP

Sector-wise risks identified for all three construction phases in the risk matrix assessment were carried forward for evaluation using the AHP. This approach addresses the quantification gap in the risk matrix method by providing judgmental criteria for tolerable risks through consistency analysis. The AHP quantifies risks by performing a relative pairwise comparison of each risk against other risks using Saaty’s scale [14].

The pairwise comparison matrix, which showcases the relative comparisons among risks, and the normalized pairwise comparison matrix are shown in **Table 1** and **Table 2**, respectively, for the feasibility study and design sector during the planning phase.

**Table 1.** Pair-wise comparison matrix for feasibility study and design sector

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Risks | Risk 1 | Risk 2 | Risk 3 | Risk 4 | Risk 5 | Risk 6 |
| Risk 1 | 1 | 3 | 5 | 7 | 3 | 5 |
| Risk 2 | 1/3 | 1 | 3 | 5 | 1/3 | 1 |
| Risk 3 | 1/5 | 1/3 | 1 | 3 | 1/5 | 1/3 |
| Risk 4 | 1/7 | 1/5 | 1/3 | 1 | 1/7 | 1/5 |
| Risk 5 | 1/3 | 3 | 5 | 7 | 1 | 3 |
| Risk 6 | 1/5 | 1 | 3 | 5 | 1/3 | 1 |
| Column Sum | 2.21 | 8.53 | 17.33 | 28.00 | 5.01 | 10.53 |

The normalized matrix is computed by normalizing the columns of the pairwise comparison matrix through the respective column sums. The vector containing the row-wise average for each risk is the eigenvector or prioritization vector. Risks are then prioritized based on the descending order of values in the eigenvector.

**Table 2.** Normalized matrix for feasibility study and design sector

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Risks | Risk 1 | Risk 2 | Risk 3 | Risk 4 | Risk 5 | Risk 6 | Eigenvector |
| Risk 1 | 0.45 | 0.35 | 0.29 | 0.25 | 0.60 | 0.47 | 0.40 |
| Risk 2 | 0.15 | 0.12 | 0.17 | 0.18 | 0.07 | 0.09 | 0.13 |
| Risk 3 | 0.09 | 0.04 | 0.06 | 0.11 | 0.04 | 0.03 | 0.06 |
| Risk 4 | 0.06 | 0.02 | 0.02 | 0.04 | 0.03 | 0.02 | 0.03 |
| Risk 5 | 0.15 | 0.35 | 0.29 | 0.25 | 0.20 | 0.28 | 0.25 |
| Risk 6 | 0.09 | 0.12 | 0.17 | 0.18 | 0.07 | 0.09 | 0.12 |

The computed eigenvector indicates that risk 1, regulatory and compliance risk, requires more attention than risk 5, land acquisition. This is followed by risk 2, improper surveying; risk 6, improper project documentation; risk 3, inaccurate traffic study; and risk 4, geopolitical instability. Note that the prioritization of these risks is based on the present case data. The AHP computations were performed across all sectors for both pre-construction and post-construction phases, and the construction phase was considered a single entity, given the uniform risk levels across its sectors. A summary of the consistency analysis is provided in **Table 3**.

The consistency analysis (refer Equations 1 and 2) contains measurement for random maximum eigenvalue (), Random Consistency (RC), Consistency Index (CI), and Constancy Ratio (CR).

(1)

(2)

The maximum eigenvalue is computed by the sum of products of the column sum and eigenvector for all corresponding risks, and random consistency is adopted based on the no. of risks (n) [14]. For a comparison to be considered reliable, the inconsistency of the comparison matrix should be less than 10%, indicating that the consistency ratio must be under 10%. This ratio is critical for the judgmental evaluation of risk assessment and determining tolerable risks.

**Table 3.** Sector-wise consistency analysis for risk assessment through AHP.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sector |  | RC | CI | CR (%) |
| Pre-Construction Phase |  |  |  |  |
| a. Feasibility Study and Design | 6.49 | 1.24 | 0.097 | 7.84 |
| b. Procurement and Tendering | 6.57 | 1.24 | 0.115 | 9.24 |
| c. Project Scheduling and Planning | 6.61 | 1.24 | 0.123 | 9.90 |
| Construction Phase | 6.51 | 1.24 | 0.102 | 8.26 |
| Post Construction Phase |  |  |  |  |
| a. Visual Inspection | 6.78 | 1.24 | 0.156 | 12.61 |
| b. Non-Destructive Evaluation | 6.56 | 1.24 | 0.113 | 9.12 |
| c. Numerical Simulations | 6.56 | 1.24 | 0.112 | 9.00 |
| d. Repair Recommendation | 9.66 | 1.41 | 0.237 | 16.78 |

The visual inspection and repair recommendation sector exhibit a consistency ratio greater than 10%, indicating an inconsistency in the pairwise comparison and indirectly suggesting higher risks in the relative comparison. Consequently, control measures must be implemented to mitigate risks in these sectors, with the aim of limiting the consistency ratio to 10%. The corresponding control measures are recommended for critical risks identified through comparative study.

1. Comparative Study

Sector-wise prioritized risks and the outcomes of risk assessments using the Risk Matrix and AHP are compared in **Table 4**. This comparative investigation provides insights into the critical risks encountered or anticipated at the site and identifies the most suitable risk assessment methodology.

In the pre-construction phase, both the Risk Matrix and AHP identified regulatory and compliance risks, land acquisition, inappropriate technology adoption, and unrealistic project schedules as significant risks. However, the Risk Matrix additionally highlighted financial risk and inadequate handling of social issues. In contrast, the AHP identified improper surveying and project clearance delays as critical risks. This discrepancy indicates that although both methods recognize key regulatory and scheduling issues, the Risk Matrix captures broader financial and social concerns, whereas the AHP emphasizes specific procedural delays and surveying issues.

During the construction phase, AHP prioritizes supply chain risk over financial risk, which is in line with the forensic investigation’s conclusion that there is a possibility of utilizing poor-quality materials. Despite this, the overall perspective from the Risk Matrix approach also aligns with AHP. Both approaches prioritized operational risk, as evidenced by on-site poor construction practices.

In the post-construction phase, the AHP prioritizes risks in a systematic and chronological manner. Due to accessibility limitations, not all distress data can be accessed, leading to inaccurate material properties. Consequently, numerical analysis with inaccurate material strength results in insufficient reinforcement details and, poor subjective interpretation. This inaccurate root cause interpretation and repair work will not stabilize the structure in the long term, potentially leading to recurrent distress. However, operational risks should be noted, as there might be a chance of poor construction practices similar to those in the construction phase. This systemic interpretation directly leads to budget overruns that result in financial risks and are indirectly linked to human error. The systematic prioritization from AHP is also highlighted through the Risk Matrix approach but in a broader manner, such as inaccurate data due to accessibility limitations resulting in financial issues. Although the Risk Matrix approach additionally prioritizes overlooking alternatives and the interruption of traffic flow, these issues indicate optimal repair works and on-site challenges from a broader perspective.

**Table 4.** Sector-wise comparison for prioritized global risks through Risk matrix and AHP.

|  |  |  |
| --- | --- | --- |
| Phase | Risk Matrix Approach | AHP |
| Pre-Construction | Land Acquisition | Regulatory and Compliance Risk |
|  | Unrealistic Project Schedule | Land Acquisition |
|  | Financial Risk | Improper Surveying |
|  | Regulatory and Compliance Risk | Inappropriate Tech. Adoption |
|  | Handling of Social Issues | Unrealistic Project Schedule |
|  | Inappropriate Tech. Adoption | Project Clearance Delays |
| Construction | Operational Risk | Operational Risk |
|  | Financial Risk | Supply Chain Risk |
|  | Supply Chain Risk | Financial Risk |
|  | Poor Coordination Risk | Poor Coordination Risk |
|  | Sub Surface Issues | Sub Surface Issues |
|  | Traffic Control Issues | Traffic Control Issues |
| Post Construction | Inaccurate Data | Accessibility Limitations |
|  | Accessibility Limitations | Inaccurate Material Properties |
|  | Financial Risk | Subjective Interpretation |
|  | Overlooking Alternatives | Operational Risk |
|  | Operational Risk | Financial Risk |
|  | Interruption of Traffic flow | Human Error |

The comparative analysis demonstrates that a risk matrix provides a quick assessment and initial information on risks from a broad perspective but can be slightly biased. Whereas, the AHP performs risk assessment through pairwise comparison, offering detailed risk prioritization in a more systematic manner. Thus, this study highlights the gross perspective of the Risk Matrix approach and the effective perspective of the AHP, recommending an integrated approach for optimal risk assessment.

* 1. Control Measures

Due to the inconsistencies observed through the AHP in the post-construction phase, control measures in terms of preventive and responsive actions are recommended in **Table 5**.

These measures can be implemented during repair and retrofitting processes to mitigate risks that have already occurred and affected the structure’s functionality, as well as risks anticipated during retrofitting processes and during future maintenance and monitoring phases post-retrofitting.

**Table 5.** The recommended control measures for the repair and retrofitting sector.

|  |  |  |  |
| --- | --- | --- | --- |
| Risk | Preventive Measures | Responsive Measures | |
| Inaccurate Data | Technical training for auditing team | | Schedule additional monthly data reviews |
| Conduct quarterly data audits | | Revise plan and additional testing |
| Accessibility Limitations | Deploy Drones for Remote Inspections | | Revise Repair Plans |
| Conduct weekly pre-inspection surveys | | Focus on critical accessibility areas |
| Overlooking Alternatives | Structural root cause analysis | | Conduct Post-Repair Inspections |
| Perform monthly contributing causes analysis | | Revaluate root causes and revise repair actions |
| Financial Risk | Establish a Realistic Schedule with key Milestones | | Analyse Cost overruns and stabilise the cause |
| Establish earned value management practices | | Explore new funding alternatives |
| Operational Risk | Timely maintenance of machinery equipment | | Implement Corrective Actions within a Month of Issue Identification |
| Perform regular Quality Control and Quality Assurance Checks | | Address Communication gaps |
| Safety Risk | Frequently updating safety protocols | | Investigate Safety Incidents within 48 Hours |
| Conduct quarterly PPE (personal protective equipment) audits | | Establish a safety audit team |
| Unforeseen Consequences | Conduct monthly engineering reviews | | Monitor repaired structure weekly |
| Simulate 5 possible failure scenarios | | Revise plan within 1 week if necessary |

Preventive measures reduce the likelihood, whereas responsive measures mitigate the impact of risks. With the application of these measures, the risk assessment through the AHP has shown improved consistency ratios, thereby ensuring acceptable levels.

The categorized risks and recommended control measures can be also applied to similar new projects from the pre-construction stage to ensure smooth construction practices, optimal structural performance and serviceability, and cost-effective financial solutions.

1. Conclusions

The study integrated forensic structural investigation data with risk assessment to enhance the evaluation and management of risks in flyover bridge projects. By utilizing both qualitative (Risk Matrix) and quantitative (AHP) approaches, this study identified and prioritized critical risks across pre-construction, construction, and post-construction phases. The developed framework, which provides an integrated risk assessment through a Risk Matrix and AHP approaches using forensic investigation data, was applied to a flyover case study. The comparative analysis reveals that while the Risk Matrix provides a quick and broad assessment, the AHP offers a systematic and detailed risk prioritization through pairwise comparisons. The critical risks prioritized by this integrated framework are linked to the root causes of distress identified in the construction phase, demonstrating the framework’s efficiency. However, the study suggests further exploration into fuzzy-based AHP for greater quantification. The critical risks identified in the post-construction phase can be mitigated by implementing the recommended control measures, focusing on retrofitting processes and future maintenance and monitoring phases post-retrofitting.

The identified risks and corresponding control measures can be utilized in similar future projects, starting from the pre-construction phase. This approach will promote efficient construction practices with safety concerns, ensure optimal structural performance and serviceability, and provide cost-effective financial solutions.

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