

Development of a Numerical Calculation-Based Bridge Asset Management System for Structural Performance Evaluation and Lifecycle Optimization

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Abstract - Bridges are critical assets in transportation networks, and their effective management is vital to ensure safety, reliability, and long-term sustainability. Traditional bridge management approaches often rely heavily on visual inspection and qualitative assessments, which may not provide sufficient accuracy for predicting deterioration or planning cost-effective interventions. To address these limitations, this research focuses on the development of a numerical calculation-based Bridge Asset Management System (BAMS) designed to enhance structural performance evaluation and lifecycle optimization for new and existing bridges.

The proposed system integrates numerical models and analytical techniques to assess bridge components, quantify structural deterioration, and estimate performance over time. By incorporating factors such as load conditions, material properties, environmental exposure, and maintenance history, the framework generates data-driven condition indices that support reliable decision-making. The use of numerical calculations also allows for the simulation of multiple maintenance and rehabilitation scenarios, enabling engineers to evaluate the long-term effects of different strategies on both cost and performance.

A key feature of this system is its emphasis on lifecycle cost analysis and optimization. By applying deterioration models and numerical performance indicators, the framework identifies the most efficient maintenance schedules that balance safety, serviceability, and budget constraints. This proactive approach reduces reliance on reactive repairs, minimizes disruptions, and ensures efficient allocation of resources. Additionally, integration with digital inventory systems enhances traceability, accuracy, and transparency in bridge asset management practices.

Ultimately, this research contributes to the advancement of innovative bridge management practices by combining engineering judgment with quantitative methodologies, ensuring safer, more durable, and cost-effective infrastructure for the future.

Keywords – Bridges, Long-term sustainability, Numerical calculation, Bridge Asset Management System (BAMS), Numerical models and Analytical techniques.

I. INTRODUCTION

Bridges are vital components of modern transportation infrastructure, serving as lifelines that connect cities, regions, and nations. Their ability to provide safe and efficient mobility underpins economic development, social integration, and trade activities. However, as the number of bridges increases and existing structures age, ensuring their reliability, safety, and serviceability has become a growing challenge. This calls for advanced bridge asset management practices that can effectively monitor, evaluate, and optimize structural performance throughout the lifecycle of these critical assets.

Traditional bridge management approaches rely heavily on visual inspections and qualitative evaluations. While these methods are essential for detecting visible signs of deterioration, they often fall short in providing precise, quantitative insights into structural performance. As a result, decisions on maintenance, rehabilitation, or replacement may be based on subjective assessments, leading to inefficient allocation of resources and, in some cases, premature failures. To overcome these challenges, there is a need for a numerical calculation-based framework that strengthens bridge condition assessment with data-driven, quantitative analysis.

A BAMS is a systematic approach that integrates inspection, condition rating, performance evaluation, and maintenance planning to ensure optimal use of resources. However, most existing systems focus on condition ratings and historical data without fully leveraging the potential of numerical modelling and analytical methods to predict structural performance. This research addresses that gap by proposing a novel calculation-based system.

Numerical methods in engineering offer a powerful means of analyzing complex behaviours of structures under different loads, environmental effects, and usage conditions. Techniques such as finite element modelling, structural reliability analysis, and deterioration modelling provide accurate predictions of how bridges respond to real-world stresses over time. By integrating these numerical approaches into bridge management systems, engineers can move beyond reactive maintenance and develop predictive and optimized strategies for asset preservation.

The development of a numerical calculation-based BAMS allows for a more scientific and objective evaluation of bridge components, including decks, piers, abutments, bearings, and foundations. Using numerical performance indicators, the system can capture both visible and hidden forms of deterioration such as cracking, corrosion, settlement, and fatigue. These outputs can then be translated into condition indices that directly feed into decision-making frameworks for maintenance prioritization and lifecycle management.

A major advantage of integrating numerical methods into BAMS is the ability to perform scenario analysis. This allows infrastructure managers to compare different maintenance strategies and choose the most cost-effective option that ensures safety while minimizing disruptions. Such scenario planning is crucial in the face of uncertainties like climate change and increasing traffic demands.

Another important aspect of this research is the emphasis on lifecycle cost analysis (LCCA). Bridges are long-term investments, and their effective management requires careful consideration of not only current repair needs but also future financial implications. Numerical calculation-based

models can estimate deterioration rates and forecast when major interventions will be required. When combined with cost models, this provides a framework for optimizing the entire lifecycle of the structure, balancing safety, serviceability, and financial sustainability.

Globally, the trend in infrastructure management is shifting toward predictive maintenance powered by digital tools, sensors, and artificial intelligence. While these technologies play a critical role, their effectiveness is significantly enhanced when combined with numerical performance models that can interpret real-time data within an engineering framework. By coupling field monitoring data with numerical predictions, the proposed BAMS framework ensures that bridge management moves toward a truly proactive and data-driven approach.

In the context of developing countries, where financial resources for infrastructure maintenance are often limited, the application of numerical calculation-based systems can have transformative impacts. Instead of allocating budgets based on subjective assessments or emergency repairs, governments can prioritize interventions based on scientifically justified indices. This ensures that limited funds are utilized where they are most needed, extending the service life of bridges and avoiding catastrophic failures.

The proposed research framework is also designed to enhance transparency and accountability in bridge management practices. By relying on quantifiable indices derived from numerical models, the system minimizes subjective decision-making. This not only improves the credibility of asset management strategies but also strengthens communication between engineers, policymakers, and funding agencies.

The integration of numerical models within BAMS also supports risk-based decision-making. For example, bridges located in flood-prone areas or subject to heavy seismic activity can be evaluated using hydrodynamic or seismic load simulations. This allows for targeted reinforcement, retrofitting, or replacement strategies based on probabilistic risk assessments, thereby improving resilience against natural disasters.

By optimizing maintenance and reducing premature replacements, numerical calculation-based BAMS contributes to resource efficiency, reduced environmental impacts, and alignment with sustainable development goals (SDGs). It encourages a shift from reactive and wasteful maintenance practices to systematic, optimized, and environmentally responsible asset management.

This research also highlights the role of digital integration in advancing bridge asset management. The proposed system can be linked with Geographic Information Systems (GIS), Building Information Modelling (BIM), and sensor-based Structural Health Monitoring (SHM) systems. Such integration ensures that inventory, inspection, numerical analysis, and performance predictions are seamlessly connected, creating a holistic management tool for decision-makers.

The practical applicability of the proposed framework will be demonstrated through case studies on selected state highways, where bridges will be assessed using the numerical calculation-based system. Performance indices, deterioration trends, and lifecycle optimization strategies will be generated to validate the model. These real-world applications will highlight the advantages of the system over traditional bridge management methods.

II. NUMERICAL MODELS AND ANALYTICAL TECHNIQUES

General

Numerical models and analytical techniques are fundamental tools in engineering for analyzing the behaviour of complex systems where exact mathematical solutions are difficult or impossible. Analytical techniques rely on mathematical equations and closed-form solutions to describe structural performance under given conditions. However, for large-scale structures like bridges, analytical methods alone are often insufficient due to nonlinearities, variable material properties, and environmental influences.

Numerical Models

Numerical models are based on the discretization of structures into smaller elements or units, enabling the simulation of their response under different loading and environmental conditions. The most widely used method is the Finite Element, which divides a bridge into nodes and elements. Numerical models also include probabilistic models, which incorporate uncertainties in material properties, traffic loads, and deterioration models, which simulate long-term performance such as corrosion or fatigue. These models are powerful for predicting structural behaviour over time and form the backbone of modern bridge asset management.

Analytical Techniques

Analytical techniques involve solving mathematical expressions derived from structural mechanics and material science. For example, equations of equilibrium, compatibility, and constitutive relations are applied to determine stresses, strains, and load capacities of bridge components. Simplified analytical models, such as beam theory or arch theory, allow engineers to derive approximate solutions for preliminary design and performance evaluation. In asset management, analytical techniques are used to establish baseline conditions, calculate load-carrying capacities, and verify results obtained from more complex numerical simulations.

Integration in Bridge Management

Analytical methods provide quick and cost-effective evaluations, especially for standard structures, while numerical models handle complex geometries, dynamic loads, and nonlinear behaviours. When integrated, they allow for accurate condition assessment, deterioration forecasting, and risk analysis. This dual approach enables infrastructure managers to make informed decisions regarding inspection, maintenance, and rehabilitation, ensuring safety and cost efficiency throughout a bridge's lifecycle.

Advantages and Theoretical Importance

The theoretical importance of combining numerical models and analytical techniques lies in their ability to transform raw data into actionable knowledge. Analytical techniques ground the system in fundamental engineering principles, while numerical models extend the analysis to real-world complexity. Together, they provide a scientific basis for performance evaluation, lifecycle optimization, and predictive maintenance strategies in bridge asset management systems. This integration reduces uncertainty, enhances reliability, and ensures sustainable management of bridge infrastructure in the long term.

III. PLANNING FOR INNOVATION

Field of the Innovation

Training Evaluation Innovation: Bridge lifecycle planning, safety evaluation, maintenance, and inspection are all included in Bridge Management Systems (BMS). From engineers to inspectors, the human element is essential.

Real-World Application Measurement: Using actual bridge performance data, real-world application measurement in Bridge Management Systems evaluates how well maintenance, inspection, and decision-making procedures work.

Skill Transfer Verification: Through training, monitoring, and performance evaluation, skill transfer verification in a bridge management system guarantees that learned technical knowledge, maintenance procedures, and inspection techniques are successfully applied, validated, and maintained for long-term infrastructure management.

Quantifiable Implementation: Measurable actions like as condition ratings, maintenance expenses, service life extension, and performance indices are all part of a bridge management system's quantitative implementation, which guarantees data-driven decision-making, accountability, and an open assessment of the efficacy of infrastructure management.

Evaluation Metrics Development: Metrics for Evaluation of order to facilitate objective performance evaluation, prioritization, and data-driven decisions for sustainable infrastructure management, development of a bridge management system creates quantifiable indicators such as condition index, lifetime cost, safety rating, and serviceability.

Adaptive Learning Enhancement: Adaptive Learning Enhancement in a Bridge Management System leverages real-time data, predictive analytics, and feedback mechanisms to continuously refine maintenance strategies, optimize resource allocation, and improve decision-making for evolving infrastructure needs.

Data-Driven Insights: Data-Driven Insights in a Bridge Management System utilize analytics, condition assessments, and performance trends to optimize maintenance, forecast deterioration, reduce costs, and support proactive, evidence-based decision-making for sustainable infrastructure management.

Performance-Outcome Linkage: Performance-Outcome Linkage in a Bridge Management System connects maintenance actions, resource use, and inspection results with service life, safety, and reliability outcomes, ensuring accountability, efficiency, and alignment with long-term infrastructure goals.

Continuous Improvement Focus: Constant Improvement in order to improve safety, prolong service life, lower costs, and accomplish sustainable infrastructure management results, focus in a Bridge Management System places a strong emphasis on iterative learning, feedback integration, performance monitoring, and process improvement.

Training Program Customization: Training Program Customization in a Bridge Management System tailors learning modules, skill development, and practical sessions to staff roles, ensuring

targeted knowledge transfer, improved efficiency, safety compliance, and sustainable infrastructure management practices.

Enhanced Training Accountability: Enhanced Training Accountability in a Bridge Management System ensures clear responsibility, progress tracking, competency validation, and performance monitoring, fostering transparency, skill retention, and effective application of training outcomes in infrastructure maintenance and management.

Background of the Innovation and Prior Art

The maintenance, inspection, assessment, and restoration of bridge structures are managed by a Bridge Management System (BMS), which is a methodical and structured methodology. throughout infrastructure authorities to guarantee that bridges continue to be secure, useful, and financially viable throughout the duration of their service lives, it is a crucial instrument. A complete management system is becoming more and more necessary as transportation networks grow and mature.

Bridges are essential parts of every transportation system because they allow traffic to flow across impediments like roads, rivers, and valleys. They cut down on travel expenses and time while promoting economic growth and connection. Given their significance, bridges require efficient planning and maintenance techniques to guarantee their continuous operation and safety.

In the past, bridge maintenance was reactive, meaning that repairs were only carried out when obvious indications of deterioration emerged. This frequently resulted in unexpected malfunctions, higher expenses, and safety risks. Authorities can now switch from reactive to preventive and predictive maintenance, guaranteeing prompt interventions and averting unplanned breakdowns, thanks to the introduction of Bridge Management Systems. Bridge infrastructure is vulnerable to early deterioration, wasteful resource use, and impaired public safety in the absence of an adequate BMS. By creating a dependable BMS architecture that guarantees long-term bridge performance, safety, and sustainability, this study or implementation initiative seeks to close this gap.

Technological innovations including sensors and Internet of Things devices for real-time monitoring, condition monitoring, and GIS (Geographic Information Systems) for mapping are all being progressively included into modern BMS solutions. These technologies offer precise, current data and insights, facilitating early structural issue detection and better-informed decision-making.

In structural engineering, the abbreviation BMS, which was first used in writing in 1987, is frequently used to refer to one or a group of digital tools and software that facilitate the documenting of all procedures pertaining to a single structure. Some of the earliest bridges ever built by mankind are believed to have been built by the ancient Mesopotamian society. To mimic natural crossings, they employed timbers, vines, and mud mortars. Later, Roman engineers used volcanic rocks to construct well-supported bridges.

Bridge structural health monitoring and assessment has been a crucial area of civil infrastructure management since the late 1980s. Two computerized platforms for viaduct inventory and monitoring, known as BMSs, PONTIS and BRIDGEIT, were funded and pushed by the US Federal Highway Administration (FHWA) in the 1990s.

Objective of the Invention

Providing an organized and data-driven method for the effective administration, upkeep, and restoration of bridge infrastructure is the aim of a Bridge administration System (BMS). Bridges are essential to transportation networks that sustain economic activity and guarantee mobility; therefore, their longevity, dependability, and safety are crucial. Through methodical planning, monitoring, and decision-making procedures, the BMS seeks to maximize these elements, guaranteeing that bridge assets continue to be secure, affordable, and operational for the general public.

Ensuring the structural integrity and safety of bridges over the course of their service life is one of BMS's main goals. Performance monitoring, condition evaluations, and routine inspections are how this is accomplished. Early detection of load-bearing problems, material deterioration, and structural flaws allows BMS to facilitate prompt maintenance and repairs, which lowers the chance of unplanned breakdowns or accidents.

The efficient use of scarce resources is another important goal. When a single agency is responsible for hundreds or thousands of bridges and maintenance finances are limited, BMS assists in determining which bridges need urgent attention. Bridges are ranked and resource allocation is guided by a combination of condition data, traffic volume, strategic importance, and danger factors. By doing this, the return on investment is maximized and resources and labour are allocated to the most important areas.

By offering resources for lifecycle cost analysis, degradation modelling, and rehabilitation projection, BMS also seeks to assist long-term infrastructure planning. These characteristics assist infrastructure managers in making well-informed choices regarding when maintenance should be done, how to prolong the life of bridges, and when replacement is required. Over time, this long-term outlook guarantees cost reductions, enhanced asset performance, and higher service standards.

Keeping an accurate and thorough inventory of all bridge assets is another goal of BMS. Structural specifications, location, design life, inspection history, load capacity, and maintenance records are usually included in this database. Such data improves accountability and openness in infrastructure management and facilitates prompt decision-making in emergency situations.

By assisting agencies in adhering to safety standards and engineering principles, the BMS also supports regulatory compliance and policy-making. It makes it possible to record budgetary results, performance indicators, and maintenance procedures all of which are useful for reporting and auditing. Additionally, by taking environmental impact into account and promoting the use of long-lasting and environmentally friendly materials, the system promotes sustainable development.

Ensuring the safe, sustainable, and economical management of bridge infrastructure is the primary goal of a bridge management system. BMS gives authorities the ability to maintain and improve bridge performance by fusing technology, data analysis, and engineering principles; this ultimately increases public safety and transportation efficiency. The success of national and regional

infrastructure strategies depends even more on a well-designed BMS as bridge networks grow and mature.

Reason for the Introduction of Bridge Management Systems (BMS)

Bridge Management Systems (BMS) were created in response to bridge collapses, especially the *Silver Bridge disaster in 1967*, which highlighted the need for better bridge management practices. At first, the focus was on creating computerized systems for inventory and monitoring. Over time, BMS evolved to encompass all facets of asset management, including resource allocation optimization and planning for inspection, maintenance, and rehabilitation.

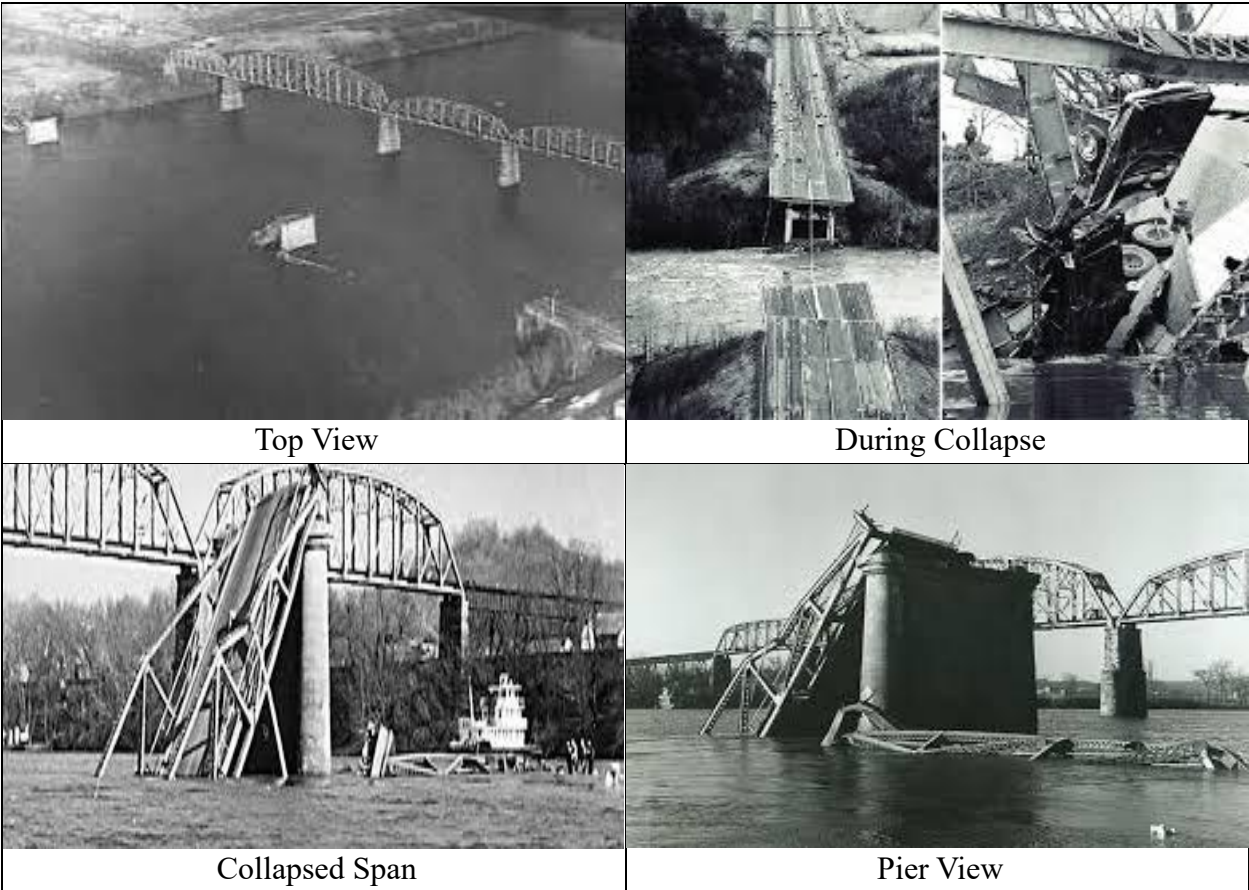


Fig. 1: Silver Bridge U.S. (source @ google)

The Silver Bridge was an eye bar-chain suspension bridge built in 1928 that carried U.S. Route 35 over the Ohio River, connecting Point Pleasant, West Virginia, and Gallipolis, Ohio. Officially named the Point Pleasant Bridge, it was popularly known as the Silver Bridge for the colour of its aluminium paint.

The Silver Bridge disaster occurred on December 15, 1967, when the eye bar suspension bridge over the Ohio River collapsed during rush hour, killing 46 people. The collapse was caused by a cleavage failure in one of the bridge's suspensions eye bars, which lacked structural redundancy. This tragedy led to the establishment of the National Bridge Inspection Standards to ensure more rigorous and routine inspections of all highway bridges in the U.S.

Source of Database and Description

Synthesis of National and International Methodologies Used for Bridge Health Indices

PUBLICATION NO. FHWA-HRT-15-081

MAY 2016

This study was conducted as part of the Federal Highway Administration's Long-Term Bridge Performance (LTBP) Program. The LTBP Program is a long-term research effort, authorized by the U.S. Congress under The Safe, Accountable, Flexible, Efficient Transportation Equity Act legislation, to collect high-quality bridge data from a representative sample of highway bridges nationwide that will help the bridge community to better understand bridge performance. This report reviews the state-of-the-art with respect to bridge condition indices being used to assess performance of bridges in the United States and other countries. This report should be of interest to bridge program personnel from Federal, State, and local transportation departments as well as to parties engaged in bridge-related research.

Bridge performance measures are important components of any successful Bridge Management System. Different types of performance measures have been developed for various purposes. The types of performance measures are usually a reflection of an agency's goals. The bridge health or condition index is a type of performance measure used by agencies interested in preserving the condition of bridge structures. Bridge condition index is very attractive because it provides a single index for assessment of the structural and or functional health of a bridge based on the condition of the bridge's structural elements and the services provided by the bridge. As outlined in the FHWA's Long-Term Bridge Performance Program, the development of condition indices should be driven by more objective and quantitative data to help bridge managers make informed decisions. This work reviews the state-of-the-art with respect to bridge condition indices being used to assess performance of bridges in the United States and other countries.

A methodology for bridge condition evaluation A methodology for bridge condition evaluation

University of Wollongong

Research Online

Faculty of Engineering and Information Sciences - Papers: Part A

Due to the substantial role of bridges in transportation networks and in accordance with the limited funding for bridge management, remediation strategies have to be prioritised. A conservative bridge assessment will result in unnecessary actions, such as costly bridge strengthening or repairs. On the other hand, any bridge maintenance negligence and delayed actions may lead to heavy future costs or degraded assets. The accuracy of decisions developed by any manager or bridge engineer relies on the accuracy of the bridge condition assessment which emanates from visual inspection.

Many bridge rating systems are based on a very subjective procedure and are associated with uncertainty and personal bias. The developing condition rating method described herein is an important step in adding more holism and objectivity to the current approaches. Structural

importance and material vulnerability are the two main factors that should be considered in the evaluation of element structural index and the causal factor as the representative of age, environment, road class and inspection is implemented as a coefficient to the OSCI (overall structural condition index). The AHP (analytical hierarchy process) has been applied to evaluate the priority vector of the causal parameter.

A STUDY OF IMAGE-BASED ELEMENT CONDITION INDEX FOR BRIDGE INSPECTION

ResearchGate

This paper presents an innovative computer vision method for condition assessments of bridges with multiple defects in bridge elements using digital images. This work utilizes 3D model of existing bridges and overlays digital images on 3D model to simulate on-site visual inspection. The analysis of element condition index (ECI) of bridges requires information about the severity and extent of defects in elements. In general, ECI is evaluated manually during routine bridge inspection considering the severity of dominant defects. The evaluation of ECI with multiple defects needs to be addressed with consideration of dominant defect as well as the interaction among defects.

However, Image-based quantification technique largely depends on geometry of objects (i.e. shapes). Shape vectors of a given object change as they are translated, rotated, and scaled with different magnitudes. This work considers shape preserving algorithms such as, affine and projective transformation for proper image alignment. Semi-automated approach for detection and quantification of concrete distress such as cracks and spalling is considered for the defects analysis. The proposed methodology ensures the consistency in reporting ECI and eliminates the shortcoming of traditional approaches.

New Jersey Department of Transportation

BRIDGE ELEMENT INSPECTION MANUAL

MAY 2, 2014 (Revision 1: January 31, 2015)

Prepared By - Structural Evaluation & Bridge Management

The proper assessment of the condition of bridge elements is the cornerstone of sound bridge management. The introduction of element inspection condition methods in the early 1990s represented a significant advancement in the bridge inspection practice and has been adopted by the New Jersey Department of Transportation. As per Section 1111 of the Moving Ahead for Progress in the 21st Century Act (MAP-21) modified 23 U.S.C. 144, each State is required to report bridge elements level data to the Secretary of FHWA. Bridge owners nationwide have recognized the benefits of detailed condition assessments through the use of the raw inspection information, expanded performance measures, and bridge management system deterioration forecasting and evaluation. As the use of element level inspection techniques has proliferated, the need for updates and enhancements to the standard element specification has been identified.

The Bridge Element Inspection Manual incorporates improvements through changes in the measurement units of decks and slabs, the development of a wearing surface element, the standardization of the number of element states, the development of protective coating elements

for concrete and steel, deck protection systems, and agency developed elements and defects. Elements constructed of innovative materials are also identified. The goal of this manual is to completely capture the condition of bridges in a simple, effective way that can be standardized across the nation while providing the flexibility to be adapted to both large and small agency settings.

RELIABILITY OF VISUAL INSPECTION OF HIGHWAY BRIDGES

F.C. Lea, C.R. Middleton CUED/D-STRUCT/TR. 201

F.C. Lea, C.R. Middleton 2002

The maintenance and preservation of bridges and consequently the safety of the travelling public depend largely on regular visual inspections of the structures. Visual inspection is, indeed, the most widely used non-destructive evaluation technique in bridge investigations. A state-of-the-practice survey carried out in the U.S.A. by Moore et al. [2001] has shown that visual inspection is the primary technique used by the largest number of respondents for inspecting concrete, steel, and timber bridges. In the U.K. routine inspections of bridges (i.e. General and Principal Inspections) are based heavily if not solely on visual examination of the structures [BD 63/94; Bridge Inspection Guide, 1983], which emphasizes the fundamental role held by the visual inspection method within the U.K. bridge assessment process.

As detailed in the Bridge Inspection Guide [1983], the effectiveness of regular visual inspections depends entirely on the bridge inspector detecting faults and problems at an early stage, and on conveying accurate, consistent, and well-recorded information to the assessing engineer who has the responsibility for deciding on any action needed. But, as Clarke [1998] pointed out, human reliability is influenced not only by a natural human proneness to make mistakes but also by performance influencing factors (i.e. factors of a system that may make errors more or less likely to occur [Whalley-Lloyd, 2001]). Therefore, the reliability of visual inspection reports depends on the bridge inspector's performance.

A review of existing inspection data from General and Principal Inspections carried out by consultants Rendel Palmer & Tritton and Taywood Engineering [1997] as part of a study on the development of a bridge condition index has highlighted that quality and consistency of visual inspection reports fall short of what should and could be achieved. Nonetheless, the maintenance and safety of bridges are often based only on the results of regular visual inspections.

This paucity of studies and lack of interest in addressing the limits of visual investigations could be explained but not justified by a number of elements.

IV. NUMERICAL CALCULATION

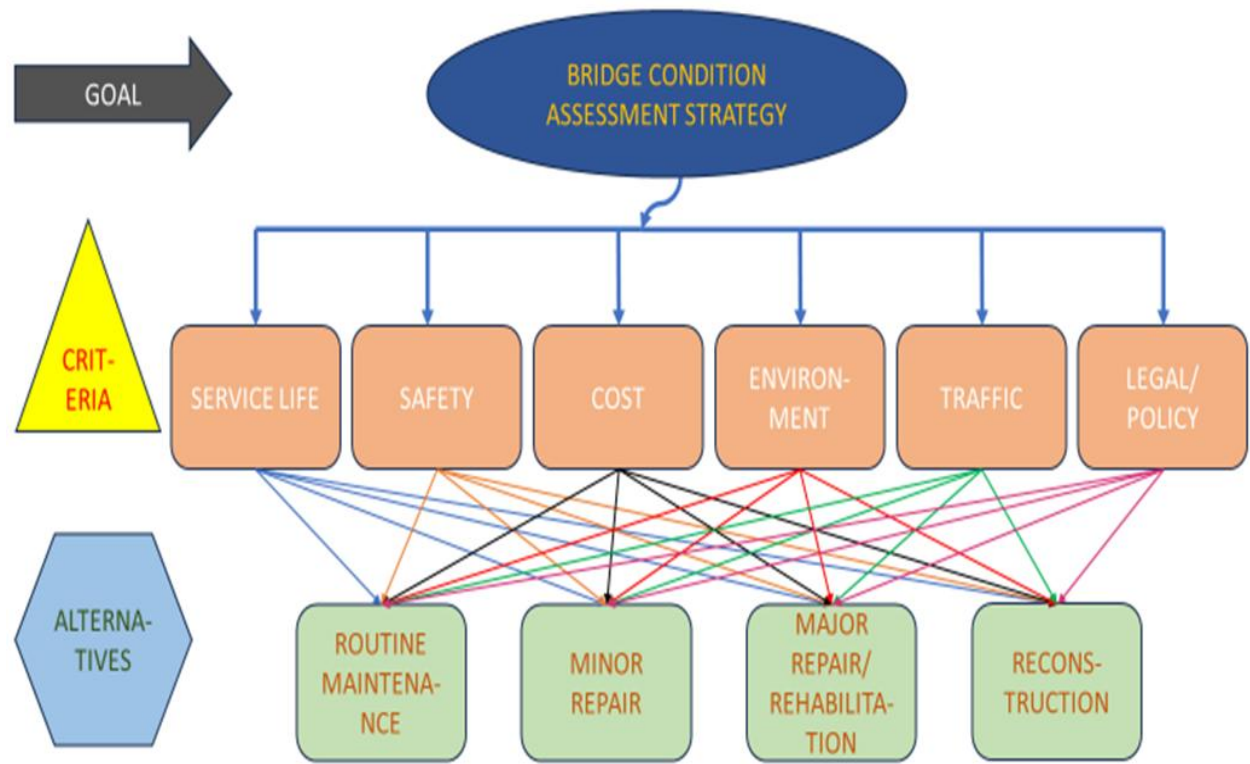
Numerical calculation in a Bridge Management System (BMS) refers to the application of mathematical and computational methods to quantify bridge performance, predict deterioration, and support decision-making. Unlike qualitative assessments, numerical calculations provide objective and reproducible values for condition ratings, load capacities, and lifecycle costs. These calculations are vital for converting inspection data, sensor measurements, and environmental influences into meaningful indices such as the Bridge Condition Index (BCI), probability of failure, or remaining service life.

There are some countries which are having their own index name and calculation Approach listed below:

Table 1: Different methods for calculating Bridge Condition

Assessment Name	Evaluation Approach
California’s BCI	Ratio Based
UK’s BCI	Weighted Average Method
South Africa’s BCI	Weighted Average Method
Austria’s BCI	Weighted Average Method
Germany’s BCI	Worst Condition Component
Japan’s BCI	Worst Condition Component

Chart 1: Bridge Condition Assessment Strategy



Bridge Condition Index (BCI) Calculation

Step I

Element Condition

Element condition in a Bridge Management System (BMS) refers to the assessment of individual bridge components such as the deck, girders, piers, abutments, bearings, and joints etc., based on their physical state and performance. Each element is inspected, rated, and assigned a condition score using standardized criteria, capturing defects like cracks, spalling, corrosion, or deformation. These element-level ratings are then aggregated to determine the overall bridge condition index (BCI), which supports maintenance prioritization, deterioration forecasting, and lifecycle management. This approach ensures that even localized issues are identified early, preventing them from escalating into major structural failures.

Result of element condition

Table 2. Amount of defect & Seriousness

Class	Amount of Defect	Seriousness	Details
0	Nil	A	Nil
1	Nil to 5% of component area	B	Indications of degradation or a little flaw
2	6% to 20% of component area	C	It's reasonable to anticipate some loss of functionality
3	21% to 50% of component area	D	The component is on the verge of failing.
4	51% to 70% of component area	E	Bridge should be closed for heavy traffic movement
5	71% to 100% of component area	F	Reconstruction

In the above table, the amount of defect refers to the extent or quantity of deterioration present in a bridge component, such as the length of a crack, the percentage of corroded reinforcement, or the area of spalled concrete. It quantifies how much of the element is affected by damage, often expressed as a percentage of the total element area or length. For example, if 20% of a deck slab shows spalling, the amount of defect is 20%.

The seriousness of defect refers to the severity and impact of the defect on structural performance and safety.

It considers how critical the damage is to the function of the bridge, whether it reduces load-carrying capacity, accelerates deterioration, or poses safety hazards. For example, minor surface cracks may have a low seriousness level, while deep cracks in a pier or severe corrosion in tension reinforcement are considered highly serious. In a Bridge Management System (BMS), both amount and seriousness are combined to assign condition ratings, which guide maintenance priorities and repair decisions.

Table 3. Result of element condition

Class		Seriousness				
	A	B	C	D	E	F
0	0.1	Not Acceptable for these				Need New Construction
1	0.2	0.3	0.4	0.5	0.6	
2	0.3	0.4	0.5	0.6	0.7	
3	0.4	0.5	0.6	0.7	0.8	
4	0.5	0.6	0.7	0.8	0.9	
5	Reconstruction					

In the above table, Class explains the Severity of each component where 0 defines new construction and 5 defines Very High distress. Seriousness values took in between 0 to 1 in fractions where 0 for new construction 0.9 for maximum limit distress while 1 is the end of bridge life.

Step II

Critical Factor

A critical factor in a bridge refers to any element, condition, or external influence that significantly affects the safety, durability, and performance of the structure. These factors determine how well a bridge can carry loads, resist environmental stresses, and serve its intended lifespan.

Some of the most important critical factors in bridges include:

1. **Structural Condition** – Integrity of key components such as deck, girders, piers, abutments, and foundations.
2. **Load Capacity** – Ability to withstand increasing traffic volumes, heavy vehicles, and dynamic forces.
3. **Material Deterioration** – Corrosion of steel, concrete spalling, fatigue, and wear that reduce strength.
4. **Hydraulic and Scour Effects** – Erosion around foundations due to river currents or floods, which is a major cause of failures.
5. **Seismic and Wind Vulnerability** – Response to earthquakes, high winds, and other natural hazards.
6. **Maintenance Practices** – Frequency and quality of inspections, repairs, and preventive measures.
7. **Design and Construction Quality** – Adequacy of initial design parameters, alignment, and workmanship.
8. **Environmental Factors** – Exposure to aggressive environments, temperature changes, and climate impacts.

In a Bridge Management System (BMS), these critical factors are monitored and analyzed to prioritize inspections, allocate resources, and plan timely interventions to avoid failures.

Table 4: Component's critical factor

Component's Severity	Values	Bridge Component
Very high	5	Deck, Girder, Arch, Bearing, all types of foundation
High	4	Substructure, Wing walls, Retaining walls
Medium	3	Handrails, Approach Slab, Wearing surface
Low	2	Drainage, Slope protection,
Nil	1	Bridge signs & Luminaries

Step III

Calculations

Overall Bridge Condition Index (BCI)

$$BCI = \frac{\text{Component Condition Value} \times \text{Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100$$

Step IV

BCI Rating

Table 5: Bridge Condition Index Rating

BCI Value	Rating
$91 \leq BCI \leq 100$	Reconstruction
$81 \leq BCI \leq 90$	Very poor
$61 \leq BCI \leq 80$	Poor
$41 \leq BCI \leq 60$	Fair
$21 \leq BCI \leq 40$	Good
$11 \leq BCI \leq 20$	Very Good
$0 \leq BCI \leq 10$	Nil

Step V

Overall, BCI Rating of bridge

High Severity components will be considered first for mentioning the overall rating of Bridge.

V. RESULTS & DISCUSSIONS

Bridge 1: Under construction Railway Over Bridge (R.O.B.)

Division: NH 107 Bihar

Section / Road Name: Maheshkhut Simri Bakhtiyarpur Saharsa Madhepura Purnea Section of NH 107

Road Classification: NH 107

Chainage (km): 91+804

Inventory Data of Bridge

River/Road/Feature Under Bridge: Saharsa Purnia Railway Line

Year of Construction & Rehabilitation/Reconstruction: Under construction

Bridge Category & Function: Major & R.O.B.

Number of Spans: 4 (1X19 + 2x38 + 1X19) m

Bridge Type & Length (m): High Level & 76

Clear Road Width (m): 9

Deck Width (Out-Out Deck Fascia) (m): 15

Left/Right Kerb Width (m): 0.50/0.50

Wearing Surface Type & Thickness (mm): Flexible (Asphaltic) & 40

Type of Railings & Height (m): RCC Crash Barrier & 0.95

Superstructure/Deck Type & Material: Composite

Abutment/Pier Material: RCC Columns

Type of Bearings & Expansion Joints: POT-PTFE & Strip Seal

Remarks: Under construction



Pile Cap



Pier Cap Shuttering



Fig. 2: R.O.B. at Madhepura Bypass on NH 107

For under-construction bridges, the Bridge Condition Index (BCI) is applied differently compared to existing or old structures. Since the bridge is not yet operational, BCI here does not measure deterioration, but rather focuses on quality control, construction compliance, and early defect detection to ensure long-term performance.

During construction, the BCI can be assessed through:

- **Material Quality Checks** – Concrete strength tests, steel reinforcement quality, curing, and mix design compliance.
- **Workmanship Evaluation** – Alignment, placement of reinforcement, compaction, finishing, and proper installation of bearings or joints.
- **Dimensional Accuracy** – Cross-checking design specifications against executed work (e.g., deck thickness, pier dimensions, span length).
- **Early Defect Identification** – Detecting cracks, honeycombing in concrete, improper welding, or foundation settlement.
- **Safety and Stability Checks** – Temporary supports, scaffolding, and load tests to ensure construction safety.

Thus, in an under-construction bridge, BCI acts as a construction quality index rather than a deterioration measure. For Under construction bridges BCI is only considered for the component which is ready. In those component/s the distresses are noted and then the final BCI Rating is mentioned as Under Construction.

Bridge 2: Sone River Bridge

Division: Rewa Madhya Pradesh

Section / Road Name: Bahri Hanumana Road

Road Classification: MDR

Chainage (km): 10+000

Inventory Data of Bridge

River/Road/Feature Under Bridge: Sone River

Year of Construction & Rehabilitation/Reconstruction: 1970 & Reconstruction

Bridge Category & Function: Major & River Bridge

Number of Spans: 42 (42X15) m

Bridge Type & Length (m): High Level & 630

Clear Road Width (m): 6.5

Deck Width (Out-Out Deck Fascia) (m): 7.5

Left/Right Kerb Width (m): 0.50/0.50

Wearing Surface Type: Rigid

Type of Railings & Height (m): RCC Flood Indicator & 0.80

Superstructure/Deck Type & Material: Multi-Beam & RCC

Abutment/Pier Material: RCC Wall

Type of Bearings & Expansion Joints: N.A. & Filler

Remarks: Reconstruction





Fig. 3: Sone River Bridge Rewa Madhya Pradesh

Table 6: Distress count in Bridge

Summary of Distress
Cracks on wearing surface were observed.
Piers were found in damaged condition due to sliding.
Major cracks were observed on span-2 & span-3.
Deflection of span 3 was observed.
Cracks were observed on cross girders on piers.
RCC railings / flood indicator were found missing.

Component 1: Foundation of the Bridge

The foundation of a bridge is the lowest and most crucial part of the structure that transfers loads from the bridge (superstructure and substructure) safely into the ground. It ensures the bridge’s stability, prevents settlement, and resists forces such as traffic loads, wind, seismic activity, and especially water currents in riverbed conditions. Since bridges are often constructed over rivers or weak soils, foundations must be designed to withstand scouring, erosion, and varying soil conditions.

Foundation was Not Visible on site and compacted by the river bed.

Hence,

BCI Rating of Foundation - Nil

Component 2: Pier/Abutment of the Bridge

A pier is a vertical structure located between bridge spans, whose primary function is to transfer loads from the superstructure (deck, girders, and traffic) down to the foundation. Piers also resist lateral forces from wind, earthquakes, and flowing water. They are typically constructed of reinforced concrete, masonry, or steel, depending on design requirements and environmental conditions. Piers must be carefully designed to minimize obstruction to river flow and resist scouring at their base. Together, piers and abutments act as the foundation’s extension, ensuring proper load distribution, structural safety, and durability.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Pier/Abutment as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 4

Seriousness E

Component Condition Value – 0.9 (From Table 3)

Component’s Severity – 5 (From Table 4)

$$\begin{aligned} \text{BCI} &= \frac{\text{Component Condition Value} \times \text{Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100 \\ &= \frac{0.9 \times 5}{5} \times 100 \\ &= 90 \end{aligned}$$

Hence, From Table 5

BCI Rating of Foundation – Very Poor

Component 3: Pier/Abutment cap of the Bridge

The pier cap and abutment cap are vital elements of a bridge’s substructure that serve as connecting components between the vertical supports (piers or abutments) and the superstructure (girders or deck). Their main function is to distribute loads evenly from the superstructure to the supporting piers or abutments and ensure structural stability.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Pier/Abutment Cap as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 2

Seriousness C

Component Condition Value – 0.5 (From Table 3)

Component’s Severity – 4 (From Table 4)

$$\begin{aligned} \text{BCI} &= \frac{\text{Component Condition Value X Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100 \\ &= \frac{0.5 \times 4}{4} \times 100 \\ &= 50 \end{aligned}$$

Hence, From Table 5

BCI Rating of Foundation – Fair

Component 4: Girder of the Bridge

A girder is one of the most important components of the superstructure of a bridge, serving as the primary horizontal support element that carries loads from the deck slab and transfers them to the piers and abutments. Essentially, girders act as the “backbone” of the bridge, ensuring stability and load distribution across the span.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Multi Beam Girder as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 5

Seriousness F

Component Condition Value – New Construction (From Table 3)

Component’s Severity – 5 (From Table 4)

$$BCI = \frac{\text{Component Condition Value X Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100$$

Calculation not required as it fall in new construction.

Hence, From Table 5

BCI Rating of Foundation – New Construction

Component 5: Cross Girder of the Bridge

A cross girder is a transverse supporting member in the superstructure of a bridge, positioned at right angles (perpendicular) to the main longitudinal girders. Its primary function is to distribute loads from the deck slab or floor system to the main girders and provide lateral stability to the bridge structure. By connecting the main girders, cross girders help ensure that the load from vehicles and pedestrians is shared efficiently, reducing the risk of overstressing any single girder.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Cross Girder as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 4

Seriousness E

Component Condition Value – 0.9 (From Table 3)

Component’s Severity – 5 (From Table 4)

$$BCI = \frac{\text{Component Condition Value X Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100$$

$$= \frac{0.9 \times 5}{5} \times 100$$

$$= 90$$

Hence, From Table 5

BCI Rating of Foundation – Very Poor

Component 6: Wearing Surface of the Bridge

The wearing surface of a bridge is the topmost layer provided over the deck slab or roadway surface to directly withstand traffic loads, abrasion, and weathering effects. Its primary purpose is to protect the structural deck from damage, distribute vehicular loads uniformly, and provide a smooth, skid-resistant riding surface for vehicles.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Pier/Abutment as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 4

Seriousness D

Component Condition Value – 0.8 (From Table 3)

Component’s Severity – 3 (From Table 4)

$$\begin{aligned} \text{BCI} &= \frac{\text{Component Condition Value} \times \text{Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100 \\ &= \frac{0.8 \times 3}{3} \times 100 \\ &= 80 \end{aligned}$$

Hence, From Table 5

BCI Rating of Foundation – Poor

Component 7: Railing/Flood Indicator of the Bridge

The railing ensures user safety, while the flood indicator ensures structural and operational safety by monitoring natural hazards, making them essential components in bridge infrastructure.

Overall Bridge Condition Index (BCI)

Taking the maximum distress of Flood Indicator as that one will be severe to whole bridge.

From site data collection of Bridge (Check Table 6)

Class 4

Seriousness D

Component Condition Value – 0.8 (From Table 3)

Component’s Severity – 3 (From Table 4)

$$BCI = \frac{\text{Component Condition Value X Component Critical Factor Value}}{\text{Component Critical Factor Value}} \times 100$$
$$= \frac{0.8 \times 3}{3} \times 100$$
$$= 80$$

Hence, From Table 5

BCI Rating of Foundation – **Poor**

Table 7: Overall BCI of each component of the Bridge

Components	Overall BCI
Foundation	Nil
Pier/Abutment	Very Poor
Pier/Abutment cap	Fair
Girder	New Construction
Cross Girder	Very Poor
Wearing Surface	Poor
Railing/Flood Indicator	Poor

Overall BCI, of Bridge – **New Construction**

VI. CONCLUSIONS

The case study implementation demonstrates that the numerical calculation-based BAMS offers a robust and practical solution for infrastructure agencies. It provides a more precise evaluation of structural health, extends service life through optimized maintenance, and supports strategic investment planning for bridge networks.

The development of a numerical calculation-based Bridge Asset Management System (BAMS) provides a significant advancement in modern infrastructure management by moving beyond traditional visual inspections and qualitative assessments. By integrating numerical models, condition indices, and lifecycle cost analysis, the system offers a more reliable, scientific, and data-driven framework for evaluating structural performance. This approach ensures that deterioration is detected early, maintenance strategies are optimized, and decision-making becomes transparent and evidence-based.

Through its ability to quantify defects, predict future performance, and simulate alternative maintenance scenarios, the framework enhances resource allocation and supports risk-based

prioritization. The inclusion of lifecycle optimization ensures not only cost-effectiveness but also sustainability by reducing premature replacements and extending service life. Ultimately, this innovative BAMS framework strengthens safety, reliability, and resilience of bridge infrastructure, offering transportation authorities a comprehensive tool for long-term asset preservation and sustainable infrastructure development.

The Development of a Numerical Calculation-Based Bridge Asset Management System represents a significant advancement in the field of infrastructure management. By combining numerical analysis, lifecycle optimization, and decision-support tools, the framework offers a reliable, transparent, and cost-effective approach to managing bridge assets. It not only enhances safety and performance but also ensures efficient resource utilization, thereby contributing to the long-term sustainability of transportation networks.

Numerical calculation in a Bridge Management System (BMS) provides a quantitative, data-driven approach to evaluating bridge performance, predicting deterioration, and optimizing maintenance. Using tools like finite element analysis, deterioration models, and lifecycle cost analysis, it converts inspection and sensor data into measurable indices. This enables reliable forecasting, efficient resource allocation, risk-based prioritization, and transparent decision-making, ultimately ensuring safety, durability, and cost-effectiveness throughout a bridge's lifecycle.

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