BRIDGE
RESILIENCE SYSTEM

TRANSGRESSING FROM BRIDGE MANAGEMENT TO BRIDGE RESILIENCE

RESEARCHED AND CONCEPT
BY

UBMS RESEARCH GROUP

TRANSGRESSING FROM BRIDGE MANAGEMENT TO BRIDGE RESILIENCE: CRITICAL IMPERATIVENESS, NECESSITY AND IMPACT ON BRIDGES

By

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PREAMBLE AND INTRODUCTION

CRITICAL NEED TO EMBRACE AND ADAPT BRIDGE RESILIENCE

Events in China and Nepal during August 2026 urge us that the "Time to Adapt for Resilience in Now".

The devastation that was witnessed in Nepal is stated to be the worst mountain related disaster in recorded history. The scale of destruction and loss of human lives keeps on mounting as days pass by. Entire villages were swept and enveloped by mud, debris and water borne sedimentation. Very few structures, bridges, roads survived in the impact

Numerous theories and scientific studies will undoubtedly examine the probable causes and impacts of the recent cross-border natural hazard events. What must be urgently recognised, is that the **cascading effect of one natural hazard triggering multiple secondary hazards is no longer a theoretical possibility— this is a reality**. In this event, the glacier collapse triggered multiple catastrophic secondary events.

Various news channels [Local and international WION, CNN, NEWS18, IGR…] were abuzz on 28 August with reports of immense infrastructure losses in Nepal, including nearly 80 bridges. Why did bridges become such an immediate focus? The answer was obvious: **loss of connectivity means an inability to reach the impact zone quickly**.

Soon, however, the headline shifted. By 30 August, the loss of human lives had taken centre stage.

At a time when declining birth rates are already pointing towards a shrinking population in many parts of the world, the value of every human life will inevitably become even more significant. The loss of each life carries not only an immeasurable human cost but also substantial socio-economic consequences. UNDRR states that one hour delay in rescue operations can lead to loss of 50 to 70 additional human lives.

These events revealed once-in-a-lifetime lessons before us. We must learn from them, adopt those lessons and incorporate them into our **standard operating procedures, planning practices and engineering design philosophies**.

Hidden beneath the visible destruction is an important question:

Where was resilience in the design and management of the bridges that collapsed?

Engineering science may need to reconsider some of the fundamental assumptions and inputs that define the design, construction and full life management of bridges and generally all infrastructure. The boundaries of safety must evolve to accommodate an increasingly accepted reality—the frequency, intensity [severity] and cascading consequences of natural hazards are dynamic and can no longer be treated as isolated or historically predictable events.

Every engineer understands that a 25-metre wall of water and debris flowing down a steep slope, with acceleration exceeding 1.35 m/s^2, can cause mass destruction to structures located in its path. The question, therefore, is not simply whether a structure can withstand the historically defined design event. The more important question is:

Can the bridge / infrastructure continue to perform its essential function when the hazard exceeds conventional design assumptions?

That is the essence of resilience.

Resilience Must Begin at the Conceptual Stage and sustain during the entire life of the bridge.

Resilience in bridge design cannot be considered merely an additional structural feature. It must be incorporated at the **conceptualisation and planning stages and sustained during the entire life-cycle**.

For bridges, this may mean adequate vertical clearance, higher approaches, elevated road networks and appropriate hydraulic and geomorphological assessments. Such planning inevitably influences the development pattern around the bridge.

When houses and other structures are constructed on higher, safer ground and floodplains are allowed to remain free of permanent development, the region itself becomes more resilient.

An empty floodplain is not wasted land. It is natural infrastructure.

Allowing rivers and floodwaters sufficient space to perform their natural functions can significantly reduce the consequences of extreme events. A non-encroaching approach to development can therefore contribute simultaneously to resilience, sustainability and longevity.

Bridges Are More Than Transportation Infrastructure

Bridges play a vital role in regional socio-economic development and stability during normal times. Their importance, however, becomes even greater immediately after a natural hazard.

Bridges provide rescue and relief agencies with assured connectivity to the zone of impact during the critical **golden hour**. Conversely, the loss of a bridge can isolate communities precisely when rapid access is most urgently required.

Every hour of delay in rescue and relief can translate into additional loss of life. UNDRR estimates that one hour delay could translate into loss of additional 50 to 70 human lives. Therefore, the consequences of bridge failure cannot be evaluated solely through the conventional financial cost of reconstruction. Quote **"At present, disaster resilience is often not prioritised because it is seen as a cost for an event that might never happen. This results in devastating impacts when disasters do occur. We need to reframe the narrative on disaster resilience, demonstrating that it is an investment and not a cost"** UNQUOTE

The **life-cycle cost of bridges must incorporate the consequences of loss of connectivity, delayed emergency response and potential loss of human life**.

When these factors are properly incorporated into life-cycle analysis, the additional investment required to create and sustain resilient bridges may no longer appear excessive. In fact, it may prove to be one of the most economically rational investments a region can make.

The Call of the Day

The lesson from recent events in China and Nepal is not simply that natural hazards can be destructive.

The deeper lesson is that **our bridge infrastructure must be designed and sustained for a world in which hazards interact, cascade and exceed historical expectations**.

Resilience must therefore move from being a desirable characteristic to becoming a fundamental criterion.

We need to give nature adequate space to perform its functions, avoid unnecessary encroachment into floodplains and hazard-prone areas, elevate critical bridge infrastructure where appropriate, maintain redundant connectivity and incorporate post-disaster functionality into engineering decisions from the very beginning.

Sustainability cannot be achieved by continuously fighting natural processes. It is achieved by **understanding them, respecting them and designing our settlements and infrastructure to coexist with them**.

The bridges we build today must not merely connect two points during normal times. They must remain—or enable rapid restoration of—connectivity when everything around them is disrupted.

That is the true meaning of resilient bridge infrastructure.

It is time to adapt. It is time to manage for resilience. It is time to move ahead from Bridge Management Systems to Bridge Resilience System.

PART A:

BRIDGE RESILIENCE SYSTEM: MANUAL AND SYSTEM IMPLEMENTATION

BRIDGE RESILIENCE SYSTEM MANUAL AND SYSTEM IMPLEMENTATION

RESEARCHED AND CONCEPT

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UBMS RESEARCH GROUP

**AUTHORS: SACHIDANAND JOSHI,
SREENATH MENON & MAYURI TUNDALWAR**

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MANUAL AND SYSTEM IMPLEMENTATION

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BRIDGE RESILIENCE SYSTEM

INNOVATED AND RESEARCHED BY

UBMS RESEARCH GROUP, INDIA AND

GLOBAL BRIDGE MANAGEMENT SYSTEM Pty, AUSTRALIA

Background: Over the last five decades, bridges all over the world have been managed using the Bridge Management System. When no other system was available, this framework for optimisation of fund allocation worked perfectly great. Since, early nineties the role of bridges in the economic development, growth and sustainability has been recognised. Along with this recognition, the need to ensure logistic connective was also felt.

Last two decades, the severity and frequency of natural hazards have seen dynamism. Rescue and relief operators all across the world, faced constraints in reaching the impact zone. Every hour delay caused incremental loss of human lives. One major contributory factor was attributed to severance in connectivity due a failed bridges. Natural hazards occurrence contributed to a very high percent of bridge collapses. Increased dynamism resulted in severe hardship to local population in the impact zone. Economic hardship coupled with sustainability issues resulted in a scenario that attracted the attention of the entire world. Disaster Risk Reduction crept into policies of many countries. United Nations constituted an office of Disaster Risk Reduction [UNDRR].

Framework vacuum: Resilient bridges crept into the jargon of bridge fraternity. Very few organisation were in sync with this aspect of the bridges. UBMS Research Group was best placed for ensuring the bridge management catered to the needs of the society. Our Bridge management system namely the Global Analytics for Bridge Management have been poised to this scenario. We submitted a Voluntary Commitment to UNDRR to work on this aspect of bridges. Enhancement within BMS followed the logical route and Global Analytics for Risk and Resilience Management was evolved. Evaluation of Risk involved can alone define the need for resilience in the bridge. Risk and Vulnerability Analysis module ensures this aspect. From being a Mono Criteria driven management system focused on Structural aspect only, a need to incorporate emerging aspects of risk assessment, financial impact and Socio-Economic impact was felt. Multi-Criteria Decision-Making module address this need. What was needed was integrating all the modules to evolve **BRIDGE RESILIENCE SYSTEM [BRS].** We integrated the duo application of GABM and GARM to introduce the Bridge Resilience System.

BRS Innovated System: UBMS Research Group along with Global Bridge Management System researched Bridge Resilience System. This innovation resulted to enhancement to exiting Bridge management system. This innovation satisfies tomorrows need of the Bridge fraternity, the Disaster Risk Reduction institutes, and Ministries of various countries to manage and maintain their bridges by proactively rendering all the bridges in the inventory to resilient bridges.

COMPARISON OF BRIDGE MANAGEMENT SYSTEM [BMS] AND BRIDGE RESILIENCE SYSTEM [BRS]		
DETAILS	**BMS**	**BRS**
Definition	Frameworks designed to facilitate the management of bridges, optimising budgets while ensuring adequate structural performance.	Framework designed to facilitate management of bridges ensuring a proactive approach to optimising budgets to facilitate enhancement of resilience and rehabilitation to ensure adequate structural performance.
Key focus	Symptoms based deterioration modelling to determine BSL, ABSL	Selection of parameter [symptoms / cause of distress / performance of bridge] based on age to define deterioration modelling to determine BSL, ABSL, MSL
Yields fund optimisation based on	BSL, ABSL and symptoms driven deterioration modelling with focus only on severity of distress. Mono-Criterion approach for fund allocation and optimisation.	Adopts Multi-Criteria Decision-Making process for fund optimisation and management. Allows user to determine weight age that defines the relationship between four criterion. Focus is on Multi-Criteria
Rehabilitation interval decision	Reactive approach to decides the Rehabilitation interventions required.	System has a Pro-active approach to define the intervention interval. Results in avoidance of increment in distress.
Results provided within the framework	Determines BSL, ABSL	Determines BSL, ABSL, MSL, IRR, RI, VI and probability of bridge survival for natural hazards occurrences
Additional processes performed	No additional process	Performs Whole life cycle cost analysis, Risk and Vulnerability Analysis, Multi-Criteria Decision-Making process, Bridge Survival probability evaluation

BMS to a holistic BRS: To empower authorities to implement Risk and Vulnerability Analysis, we published the much needed Guideline document which could guide authorities to implement Risk and Vulnerability Analysis. Explaining the basic concept of resilience in bridges, evaluation of vulnerability, relationship between vulnerability and risk, the guideline is self explanatory document. Guideline for implementation of Risk and Vulnerability Analysis for Bridges is available on PreventionWeb of UNDRR and our website:
https://ubmsresearchgroup.com/publications/guidelines-for-implemetation-of-risk-and-vulnerability-analysis-for-bridges/

Post publication of the guidelines, we implemented a Pilot Project exactly following the steps outlined in our Guidelines, in the district of Kolhapur. Results of the same in the form of a Technical paper [Co-authored by Dr. Prasad Sankpal, a District Disaster Management officer from Kolhapur] and Project report was published and is available on PreventionWeb of UNDRR and our website:

https://ubmsresearchgroup.com/publications/compilation-on-rva-leading-to-resilience-of-bridges/

Kolhapur district immensely benefited from the pilot project and the findings and report submitted in February 2026 is under study to launch a study encompassing the full district of Kolhapur. The district authorities were impressed by the finding and the Proactive approach of the system adopted which will assist them to identify bridges in need of enhancement in resilience.

BRS incorporate futuristic technologies: Evolution of Bridge Resilience System was a journey that was long, arduous and supported by various organisations, individuals and our entire research team.

Bridge Resilience System is the result of long research journey over the past 23 years. Various researchers contributed to the evolution totalling to more than 250,000 hours of tenacious and persistent research. We present here a summary of the various techniques, technologies and theories that have contributed to this evolution, resulting in conversion of the Bridge Management System to a holistic state of art **Bridge Resilience System [BRS].**

SUMMARY OF BRIDGE RESILIENCE SYSTEM		
FUNCTIONALITY	**THEORIES, TECHNIQUES & TECHNOLOGIES**	**RESEARCH BASED ON**
Data collection, acquisition and processing.	Finite Element Analysis[FEM], Machine Learning based Artificial Learning. Convolution Neural Network.	377 References
	Global Positioning System, HTTP protocol, MySQL, Dot net techniques, Large scale Big-Data processing tools, Cloud storage, Common Data Environment for information management, 3D photogrammetry tools	
Bridge Deterioration modelling	Stochastic and Deterministic methods using Markov Chain model, Probability methods, Weibull distribution models, Bayesian Belief Networks, Reliability based theories are all integrated within the Machine learning protocol to select the input data based on age of the bridge.	1375 References
	Corrosion theory, Environmental impact studies, Age related Fatigue analysis are combined within the Machine learning protocol. Structural mechanics and basic physical theories	
Balance Service life, Absolute Balance Service life and Median Service life	Deterioration theories like Stochastic and Deterministic methods using Markov Chain model, Probability methods, Time based reliability theory, Probabilistic design theory. Markov Chain approach modelling of bridge condition to predict likelihood of bridge components moving from one state of deterioration to the next. Grey relational analysis to overcome insufficient data situation and finally Bayesian theory.	1725 References
	Corrosion theory, Environmental impact studies, Age related Fatigue analysis are combined within the Machine learning protocol. Structural mechanics and basic physical theories integrated with basic structural mechanics and load transfer theories.	
Internal Rate of Return evaluation	Basic Life cycle cost analysis [LCCA] principles applied to whole life of the Bridge. Evaluation of Time value of money, Net present valuation, Socio-Economic impact analysis, Structural reliability theory.	95 References
	Monte Carlo Simulation techniques applied to investments, maintenance schedules formulation,	

	repair intervention cycle determination in conjunction with end of life prediction. User cost estimation and evaluation of benefits to whole region.	
Efficiency of Rehabilitation Interventions	Structural Reliability theory, Limit state function theory, Evaluation of reliability index to determine the efficiency.	60 Reference
	Bayesian decision theory in combination with Markov Deterioration modelling applied to optimisation theories. All techniques used in LCCA.	
Risk and Vulnerability Analysis of Bridges	Probabilistic risk assessment, MCDM techniques, Fragility analysis, Monte Carlo techniques, Deterioration modelling techniques, Structural analysis techniques, Limit state function theory, material science principles. Machine learning approach to Artificial Intelligence.	1850 Reference
	Weighted Multi factor modelling techniques, [Index based methods], Fuzzy and logic theories, Probabilistic theories, Fuzzy Analytical Hierarchy process techniques, Resilience assessment techniques, FEM, Decision making processes, Structural mechanic theories, Geo-Hazard integration with structural analysis.	
Short Term Structural Health Monitoring	Vibration based monitoring by Modal Analysis theory. Operational Modal Analysis, Stochastic theory to estimate deterioration, Bayesian theory.	670 Reference
	Frequency domain decomposition techniques, data based anomaly detection technique, Time series analysis applied with statistical tools. FEM and structural mechanics theories. Machine learning applied AI tools.	
Multi Criteria Decision Making Process to Bridge Resilience System	Value of money theories, Multi Attribute Utility theory, Fuzzy theory, Bayesian decision theory, Value engineering techniques.	1150 References
	Analytical Hierarchy Process [AHP], Multi Attribute Utility Theory [MAUT], Fuzzy- AHP, Technique for Order of Preference by Similarity to Ideal Solution [TOPSIS], Data Envelopment Technique. Hybrid MCDM modelling using Fuzzy AHP. Allocation of KPI [Weight assignment to performance indicator or main attributes in MCDM].	

DELIVERABLES FROM BRIDGE RESILIENCE SYSTEM	
Data collection, acquisition and processing.	Entire database of all bridges captured and stored over years when Inspection is carried out. Provides historical narrative for all variable functionalities of BRS.
Bridge Deterioration modelling, Balance Service life, Absolute Balance Service life and Median Service life	Provides important results that conventional Bridge Management System provides but based on age of bridge. Median Service Life evaluation enables probability estimation of the efficiency of rehabilitation interventions. Provides a **Proactive approach to BMS**. Application of Machine learning and Artificial Learning tools enable BRS to provide predictive maintenance scenarios that enhance the resilience of the bridge.
Risk and Vulnerability Analysis of Bridges	Provides results for the most important parameter of Enhancing Resilience in bridge by determination of vulnerability and resultant risk the bridge faces for four main natural hazards that result in Bridge failure. Also provides a probability of bridge survival scenario for the four natural hazards based on structural status of the bridge and the severity of natural hazard occurrence. Machine learning and Artificial Learning tools enable BRS to link the past occurrence of natural hazards and predict the behaviour of the bridge if similar events were to occur in future. This behaviour dictates the multi dimensional estimation of Risk and Vulnerability.
Multi Criteria Decision Making Process to Bridge Resilience System	Provides a Proactive approach and financial logic to fund allocation and fund optimisation by determination of bridge that should be provided funds and those that do not provide financial benefits to warrant fund allocation. System provides a sound financial due diligence during fund optimisation.

Journey to safety and resilient regions: UBMS Research Group and Global Bridge Management Systems have empowered Group of Bridge Inspection teams in various geographies to master the science and art of evaluation of Bridge resilience. Bridge inspection teams together with UBMS Research Group create an ecosystem. Such an ecosystem will be an ideal stage for authorities to redefine their concept of managing the inventory of bridges. Implementation of Risk and Vulnerability evaluation will ensure sustainable and resilient logistics corridors, which would lead to cost efficient deliverance of a stable, growth focused regions. Disaster Risk Reduction institutes and various disaster management department will find easier to implement efficient rescue and relief operations.

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IMPLEMENTATION OF BRIDGE RESILIENCE SYSTEM [BRS]

➢ INTRODUCTION TO BRIDGE RESILIENCE SYSTEM

The Bridge Resilience System [**BRS**] is an integrated digital platform developed for Bridge management and Bridge Resilience. This platform comprises of bridge inventory, inspection monitoring, risk assessment, resilience evaluation, and rehabilitation planning modules. The system supports bridge authorities in managing bridge infrastructure using technical, financial, and analytical tools within a centralized framework. BRS helps in identifying bridge vulnerabilities, evaluating deterioration conditions, and improving long-term infrastructure safety and sustainability. The platform also supports decision-making for maintenance prioritization, fund optimization, and resilience enhancement against climate change and natural hazards. Overall, BRS provides a systematic and technology-driven approach for modern bridge infrastructure management and resilience planning.

1. Overview of Bridge Resilience System [BRS]

The Bridge Resilience System [BRS] is an advanced digital platform developed for Bridge management and Bridge Resilience. The system integrates engineering, financial, environmental, and operational data into a single framework to support efficient bridge management. BRS enables bridge authorities and infrastructure agencies to monitor bridge performance, evaluate vulnerabilities, and improve long-term infrastructure sustainability. The platform also supports data-driven decision-making for maintenance, rehabilitation, and resilience enhancement activities.

2. Need for Digital Bridge Management

Traditional bridge management practices are largely dependent on manual documentation, isolated inspections, and fragmented data storage systems. With increasing bridge inventory, traffic demand, and environmental challenges, digital bridge management has become essential for efficient infrastructure governance. A digital platform improves data accessibility, inspection accuracy, reporting efficiency, and coordination between stakeholders. It also enables real-time monitoring, centralized information storage, and automated analytical processes. Digital bridge management therefore supports faster, more reliable, and technically sound decision-making.

3. Ageing Infrastructure Challenges

Many existing bridges have exceeded or are approaching their intended design life and are continuously exposed to increasing traffic loads and environmental deterioration. Ageing bridges commonly experience corrosion, cracking, spalling, fatigue, bearing failures, and foundation deterioration. These conditions gradually reduce structural capacity, durability, and operational safety. Inadequate maintenance and delayed rehabilitation further increase the vulnerability of such bridges. The management of ageing bridge infrastructure therefore requires systematic inspection, performance evaluation, and resilience-focused intervention strategies.

4. Impact of Climate Change on Bridge Networks

Climate change has significantly increased the frequency and severity of natural hazards such as flooding, cyclones, landslides, earthquakes, and extreme rainfall events. These environmental conditions directly affect bridge performance, safety, and durability. Changes in river flow, scour conditions, temperature variation, and moisture exposure accelerate bridge deterioration and increase the probability of structural damage. Climate-related disruptions can also impact transportation continuity and emergency response operations. Therefore, bridge management systems must incorporate climate resilience and hazard vulnerability assessment into infrastructure planning and decision-making processes.

5. Importance of Resilient Transportation Systems

Transportation bridges are critical infrastructure assets that support mobility, trade, economic growth, emergency services, and public connectivity. Failure or closure of important bridges can severely disrupt transportation networks and affect rescue and relief operations during disasters. Resilient transportation systems are designed to maintain functionality during and after hazard events while minimizing operational disruptions. Resilience-based bridge management focuses on preparedness, adaptability, rapid recovery, and long-term sustainability. Such systems ensure improved public safety, economic stability, and continuity of essential services.

6. Objectives of BRS Implementation

The primary objective of implementing the Bridge Resilience System is to establish a comprehensive and technology-driven framework for bridge management and resilience planning. The system aims to improve bridge safety, optimize maintenance planning, enhance risk assessment capabilities, and support financial decision-making. BRS also focuses on identifying vulnerable bridges, prioritizing rehabilitation measures, and improving infrastructure sustainability. The platform supports integration of inspection data, hazard analysis, resilience assessment, and lifecycle costing into a unified analytical environment. Overall, the system is intended to improve the efficiency, reliability, and long-term performance of bridge infrastructure management.

7. Scope of the BRS Platform

The BRS platform covers the complete lifecycle management of bridge infrastructure from registration and inventory development to resilience enhancement and financial planning. The system includes modules for bridge identity management, inspection recording, distress assessment, risk and vulnerability analysis, rehabilitation estimation, resilience evaluation, and dashboard monitoring. It also supports geospatial mapping, hazard zoning, analytical reporting, and fund optimization processes. The platform integrates technical, operational, financial, and environmental aspects into a centralized management system. This broad scope enables efficient bridge asset management at project, regional, and national levels.

Stakeholders and User Roles

The Bridge Resilience System involves multiple stakeholders including bridge authorities, inspection engineers, infrastructure administrators, consultants, financial analysts, and policy makers. Different user roles are defined within the system to ensure secure access and controlled operational responsibilities. Administrative users manage regional and organizational activities, while technical users perform inspections, assessments, and analytical evaluations. Decision-makers utilize the system outputs for prioritization, budgeting, and resilience planning. The defined user hierarchy improves accountability, coordination, workflow efficiency, and secure data management within the BRS platform.

Definition of Critical Routes

Before embarking on implementation of Bridge Resilience System, it is essential to study the map of the region. This study should result in clear identification of routes and roads that can be termed **CRITICAL ROUTES.** Such critical routes are identified as those that enables Rescue and relief operations agencies to reach most of the highly populated and important areas in the region. All bridges on this critical routes will essentially be required to be safe in the post occurrence scenario. It implies that these bridges have high resilience.

Users are requested to refer to appropriate screens on the System and details / definitions for the same in the Manual section of the document.

The work flow for implementing BRS essential will need the Users to follow the outlined procedure:

➢ BRIDGE INVENTORY AND REGISTRATION MANAGEMENT

a] Bridge Registration Framework

This section defines the procedure for registering bridge assets within the Bridge Resilience System and creating the initial bridge inventory database.

b] Bridge Identity Number Generation

The Bridge Identity Number Generation module creates a unique identification code for each bridge based on region, road type, and bridge sequence.

c] Geospatial and Location Mapping

This section captures geographical coordinates, regional information, and bridge location details for GIS-based mapping and hazard evaluation.

d] Bridge Classification and Categorization

The Bridge Classification module categorizes bridges based on road classification, structural type, operational importance, and functional characteristics.

e] Bridge Geometry and Structural Data Collection

This section records important bridge geometry and structural parameters including spans, length, foundation type, pier details, reinforcement information, and superstructure configuration.

f] Traffic and Functional Data Integration

The Traffic and Functional Data Integration module captures operational parameters such as traffic lanes, load capacity, and roadway functionality.

g] Historical Bridge Data Management

This section maintains historical information related to bridge construction, inspections, maintenance, rehabilitation, and previous condition assessments.

h] Digital Inventory Database Creation

The Digital Inventory Database Creation module integrates all bridge-related information into a centralized digital management system for monitoring and analysis.

➢ BRIDGE INSPECTION AND CONDITION ASSESSMENT

a] Inspection Methodology and Workflow

This section defines the systematic inspection process adopted for bridge condition evaluation, distress identification, and analytical assessment within the BRS platform.

b] Visual Inspection Procedures

The Visual Inspection Procedures module provides guidance for identifying visible bridge defects, deterioration symptoms, and structural deficiencies during inspections.

c] Structural Distress Identification

This section enables the identification and documentation of structural distress such as cracking, spalling, corrosion, deformation, and bearing failures affecting bridge components.

d] Damage Severity Classification

The Damage Severity Classification module categorizes identified bridge distress based on severity levels and structural impact conditions.

e] Functional and Structural Rating System

This section evaluates bridge performance using structural, functional, and socio-economic rating methodologies integrated within the BRS analytical framework.

f] Inspection Data Recording and Validation

The Inspection Data Recording and Validation module supports accurate entry, verification, storage, and management of bridge inspection information within the digital platform.

g] Image and Document Upload System

This section allows users to upload inspection photographs, technical reports, and supporting bridge documents into the BRS database for analytical and verification purposes.

h] Inspection Reporting and Compliance

The Inspection Reporting and Compliance module generates bridge inspection reports and supports compliance monitoring for maintenance, assessment, and rehabilitation activities.

➢ DETERIORATION AND PERFORMANCE EVALUATION

a] Deterioration Mechanisms in Bridges

This section explains the various deterioration processes affecting bridge components such as corrosion, cracking, spalling, fatigue, and material degradation.

b] Exposure Condition Assessment

The Exposure Condition Assessment evaluates environmental and operational conditions influencing bridge deterioration and vulnerability.

c] Material Degradation Analysis

This module focuses on evaluating the deterioration and performance reduction of construction materials used in bridge components.

d] Structural Capacity Evaluation

The Structural Capacity Evaluation assesses the ability of the bridge to safely sustain operational and environmental loading conditions.

e] Superstructure and Substructure Assessment

This section evaluates the condition and performance of superstructure and substructure elements including decks, girders, piers, abutments, and foundations.

f] Bearing and Foundation Performance Review

The Bearing and Foundation Performance Review evaluates the operational condition, stability, and functionality of bearings and foundation systems.

g] Performance Rating Methodology

This module defines the methodology used for assigning structural, functional, and socio-economic performance ratings to bridge assets.

h] Service Life Assessment

The Service Life Assessment estimates the remaining operational life of bridge components based on deterioration conditions, inspection findings, and performance indicators.

➢ RISK AND VULNERABILITY ASSESSMENT

a] Hazard Identification Framework

This section identifies natural and environmental hazards affecting bridge infrastructure such as flooding, earthquakes, cyclones, and landslides.

b] Flood Vulnerability Assessment

The Flood Vulnerability Assessment evaluates bridge exposure to flooding, hydraulic impact, scour conditions, and water-related structural risks.

c] Earthquake Risk Evaluation

This section assesses bridge vulnerability to seismic activity based on seismic zoning, structural characteristics, and exposure conditions.

d] Cyclone and Wind Hazard Analysis

The Cyclone and Wind Hazard Analysis evaluates bridge exposure to high wind pressures, cyclone impacts, and environmental loading conditions.

e] Landslide and Scour Vulnerability

This section evaluates risks associated with landslide activity, slope instability, foundation scour, and soil-related failures affecting bridge stability.

f] Exposure and Criticality Assessment

The Exposure and Criticality Assessment evaluates bridge importance, operational dependency, hazard exposure, and strategic significance within the transportation network.

g] Risk Index Development

This section defines the methodology used for calculating bridge risk indices based on hazard exposure, vulnerability, deterioration, and criticality parameters.

h] Vulnerability Rating and Prioritization

The Vulnerability Rating and Prioritization module classifies bridges based on overall vulnerability and supports prioritization for rehabilitation and resilience enhancement activities.

➢ RESILIENCE ANALYSIS AND ENHANCEMENT

a] Bridge Resilience Principles

This section defines the fundamental principles adopted for improving bridge durability, adaptability, recovery capability, and operational continuity under hazard conditions.

b] Resilience Performance Indicators

The Resilience Performance Indicators module evaluates bridge performance based on structural stability, functionality, hazard resistance, and recovery capability.

c] Failure Mode Identification

This section identifies potential structural and operational failure mechanisms affecting bridge performance under deterioration and hazard conditions.

d] Resilience Enhancement Measures

The Resilience Enhancement Measures module defines rehabilitation and resilience improvement strategies for reducing bridge vulnerability and improving long-term performance.

e] Rehabilitation and Strengthening Options

This section provides rehabilitation and strengthening solutions for improving bridge structural capacity, durability, and hazard resistance.

f] Adaptation Strategies for Climate Change

The Adaptation Strategies for Climate Change module evaluates resilience approaches for minimizing bridge vulnerability against changing environmental and climatic conditions.

g] Structural Redundancy and Recovery Planning

This section evaluates bridge redundancy, operational backup capacity, and recovery planning strategies following hazard events or structural failures.

h] Resilience Scoring Framework

The Resilience Scoring Framework defines the methodology used for evaluating and assigning resilience scores based on bridge condition, vulnerability, hazard exposure, and recovery capability.

➢ FINANCIAL ANALYTICS AND FUND OPTIMIZATION

a] Capital Cost Estimation

This section evaluates the estimated construction and replacement cost of bridge assets based on bridge dimensions, configuration, and structural characteristics.

b] Rehabilitation Cost Analysis

The Rehabilitation Cost Analysis module estimates the financial requirements for repair, strengthening, resilience enhancement, and rehabilitation activities.

c] Annual and Periodic Maintenance Costing

This section evaluates annual and periodic bridge maintenance costs based on predefined maintenance percentages and operational requirements.

d] Lifecycle Cost Assessment

The Lifecycle Cost Assessment module evaluates long-term bridge expenditure associated with maintenance, rehabilitation, operation, and resilience enhancement activities.

e] Budget Allocation Strategies

This section defines methodologies for allocating available bridge maintenance and rehabilitation budgets based on risk, vulnerability, and infrastructure priorities.

f] Financial Risk Evaluation

The Financial Risk Evaluation module assesses financial exposure associated with bridge deterioration, hazard vulnerability, rehabilitation delays, and operational disruptions.

g] Multi-Criteria Decision-Making [MCDM]:

This section supports decision-making by integrating technical, financial, risk, and socio-economic parameters for bridge prioritization and fund optimization.

Introduction to Multi-Criteria Decision-Making (MCDM)

Bridge management has evolved significantly from condition-based inspection systems to advanced resilience-oriented decision-support systems. Modern bridge infrastructure management requires simultaneous consideration of structural safety, resilience, economic efficiency, social importance, environmental exposure, and vulnerability to natural hazards. Decision-making based solely on structural distress is no longer sufficient for managing bridge networks exposed to increasing climate risks and budget constraints.

The Bridge Resilience System (BRS) incorporates a Multi-Criteria Decision-Making (MCDM) framework to support infrastructure owners, bridge authorities, and decision-makers in prioritizing rehabilitation, resilience enhancement, and fund allocation activities. The MCDM framework enables evaluation of multiple competing criteria simultaneously and provides a transparent, technically justified, and financially optimized prioritization process.

The objective of MCDM within BRS is to ensure that bridge management decisions are not based on a single parameter but instead consider the complete bridge ecosystem including structural condition, vulnerability exposure, resilience requirements, financial implications, and socio-economic importance.

Evolution from Condition-Based Assessment to Resilience-Based Decision-Making

Traditional bridge management systems focused primarily on identifying symptoms of distress and allocating maintenance funds to bridges exhibiting severe deterioration. While this approach addressed immediate structural concerns, it often overlooked long-term resilience requirements, vulnerability to natural hazards, and socio-economic consequences associated with bridge failures.

Advancements in bridge engineering, deterioration modelling, Structural Health Monitoring (SHM), Life Cycle Cost Analysis (LCCA), and Risk and Vulnerability Assessment (RVA) have transformed bridge management into a comprehensive decision-support process. Modern bridge management requires consideration of not only the current structural condition but also future performance, climate resilience, hazard exposure, operational continuity, and economic sustainability.

The BRS platform therefore integrates analytical outputs generated from multiple modules including deterioration assessment, risk assessment, resilience evaluation, lifecycle costing, and socio-economic analysis into a unified decision-making framework.

Role of MCDM within Bridge Resilience System

The MCDM framework acts as the final integration layer within the Bridge Resilience System. Information generated through bridge inventory, inspection, deterioration evaluation, risk assessment, resilience analysis, and financial analytics is consolidated to support prioritization of bridge interventions.

The framework enables bridge owners and decision-makers to answer critical questions such as:

- Which bridge should receive rehabilitation funding first?
- Which bridge requires resilience enhancement before the next hazard event?
- Which bridge presents the highest operational risk?
- Which bridge generates the highest socio-economic impact?
- Which bridge provides the best return on investment?
- Which bridge contributes most significantly to network continuity during emergencies?

By integrating answers to these questions, the system develops a comprehensive priority ranking for bridge intervention and investment planning.

h] Fund Optimization Techniques

The Fund Optimization Techniques module evaluates efficient utilization of available financial resources for maximizing bridge rehabilitation and resilience outcomes.

BRIDGE ANALYTICAL RESULTS AND RESILIENCE EVALUATION REPORT

The Bridge Resilience System [BRS] is an advanced and integrated bridge management platform developed to support bridge inventory management, structural assessment, resilience evaluation, risk and vulnerability analysis, rehabilitation planning, lifecycle cost evaluation, and financial optimization. The platform integrates engineering parameters, operational conditions, environmental exposure, hazard vulnerability, socio-economic importance, and resilience indicators into a unified analytical framework for comprehensive bridge management and decision-making.

The BRS analytical framework enables bridge authorities and infrastructure agencies to evaluate the current condition, deterioration status, vulnerability exposure, resilience capability, and rehabilitation requirements of bridge infrastructure assets. The system also supports prioritization of bridges based on structural condition, operational importance, hazard exposure, financial impact, and resilience performance.

The analytical outputs generated through BRS provide detailed insights into Bridge Safety Level [BSL], Absolute Balance Service Life [ABSL], Median Service Life [MSL], Risk Index, Sustainability Index, Engineering Impact Index, Financial Impact Index, Lifecycle Cost Analysis [LCCA], Internal Rate of Return [IRR], and resilience evaluation parameters. These outputs support informed decision-making and optimized allocation of rehabilitation and maintenance resources.

1. GRAPHICAL OUTPUTS AND ANALYTICAL VISUALIZATION

The Bridge Resilience System generates graphical outputs and analytical visualizations for improved interpretation of bridge performance, deterioration progression, and resilience evaluation results.

The graphical outputs include:

1. BSL and ABSL Trend Graphs
2. Risk Index Visualization
3. Vulnerability Assessment Charts
4. Lifecycle Cost Analysis Graphs
5. Engineering and Financial Impact Graphs
6. Resilience Performance Charts
7. Priority Ranking Visualization
8. Hazard Exposure Distribution Graphs

These visual outputs improve analytical understanding and support effective technical presentations, reporting, and infrastructure management decision-making.

2. RECOMMENDED INTERVENTIONS AND RESILIENCE ENHANCEMENT

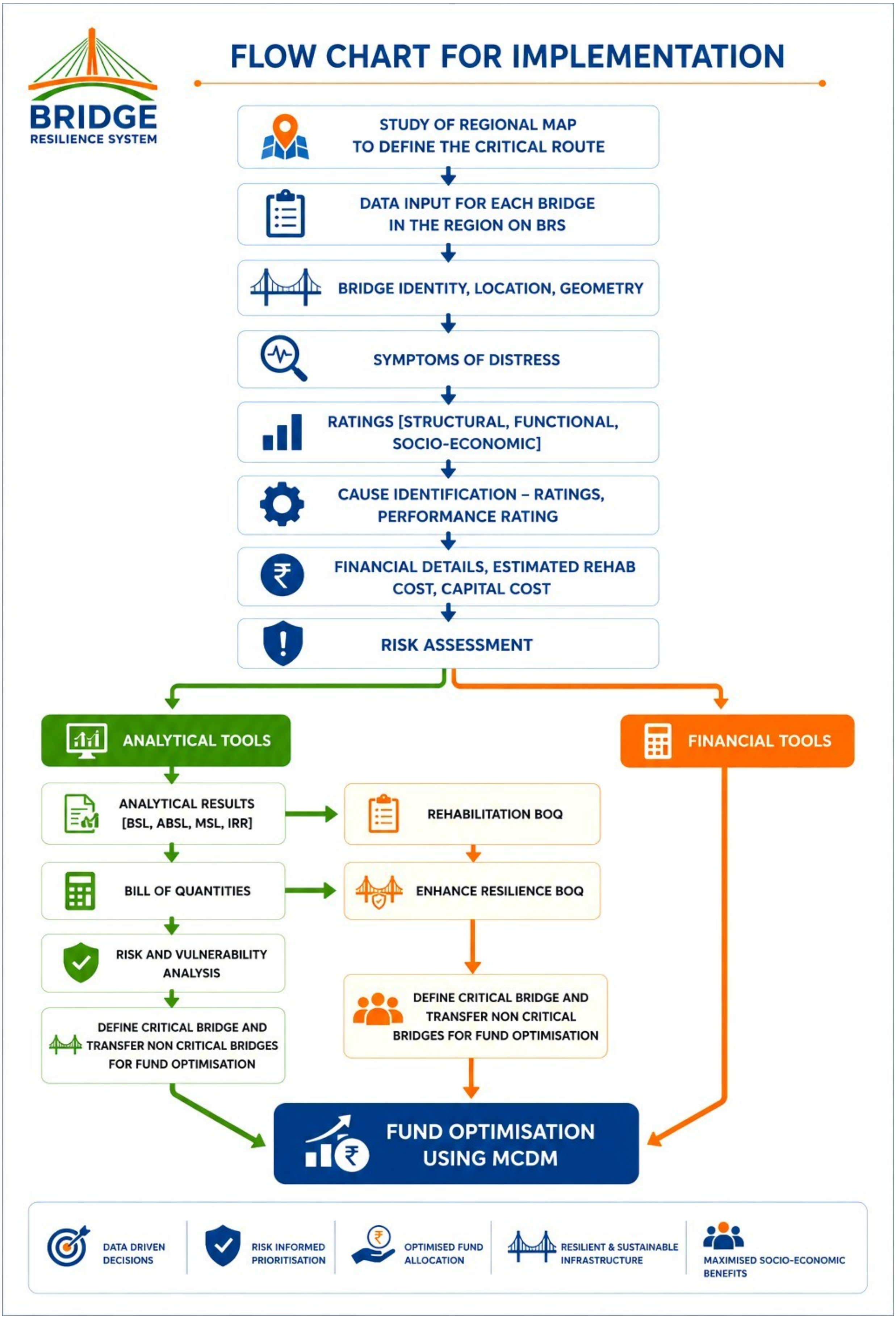
Based on the analytical outputs generated through the BRS platform, the system provides recommendations for rehabilitation, structural strengthening, monitoring, and resilience enhancement.

The recommended interventions include:

1. Concrete Restoration
2. Structural Strengthening
3. Bearing Replacement
4. Foundation Stabilization
5. Scour Protection
6. Rehabilitation and Repair Measures
7. Hazard Mitigation Strategies
8. Monitoring and Observation Requirements

The system also evaluates the efficiency of rehabilitation interventions and estimates incremental rehabilitation costs associated with enhanced resilience and safety requirements.

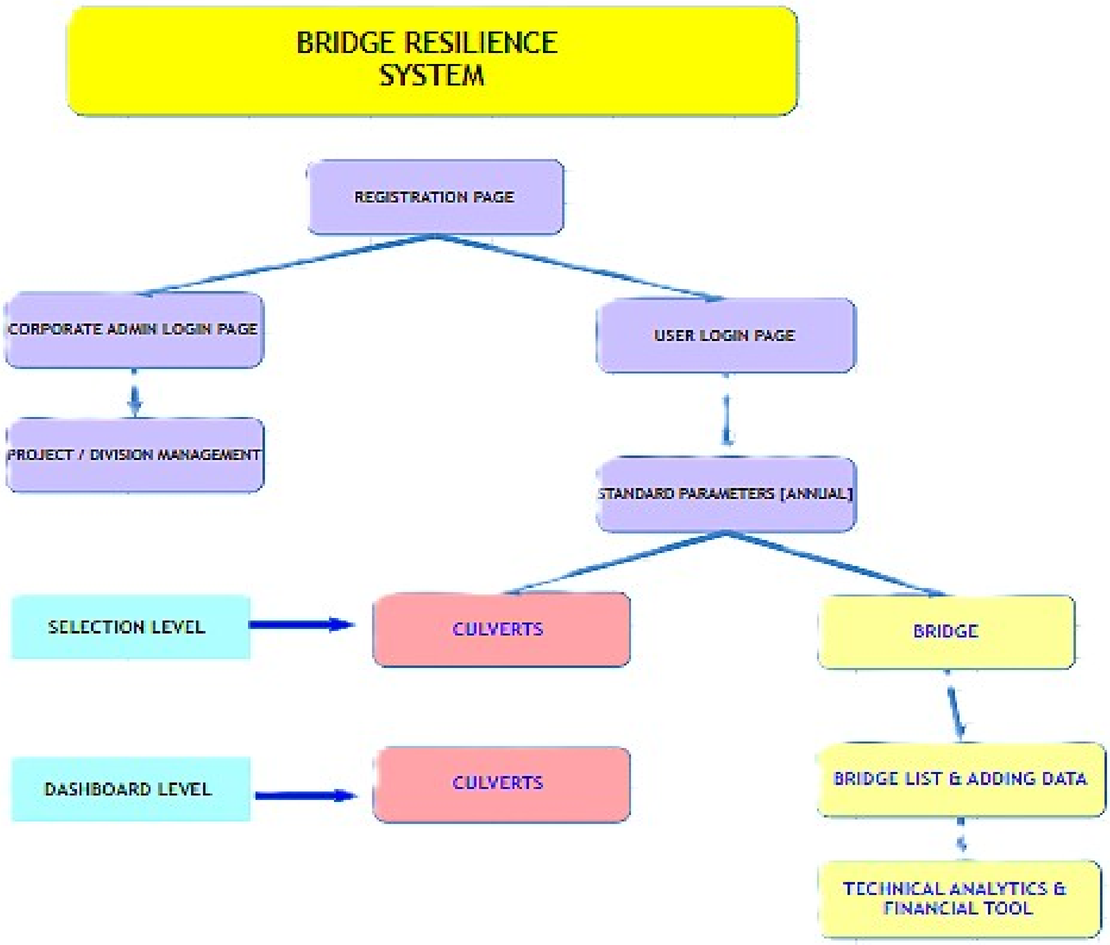
These recommendations support bridge authorities in implementing sustainable and resilience-oriented infrastructure management strategies.


BRIDGE
RESILIENCE SYSTEM
FLOW CHART FOR IMPLEMENTATION
STUDY OF REGIONAL MAP
TO DEFINE THE CRITICAL ROUTE
DATA INPUT FOR EACH BRIDGE
IN THE REGION ON BRS
BRIDGE IDENTITY, LOCATION, GEOMETRY
SYMPTOMS OF DISTRESS
RATINGS [STRUCTURAL, FUNCTIONAL,
SOCIO-ECONOMIC]
CAUSE IDENTIFICATION – RATINGS,
PERFORMANCE RATING
FINANCIAL DETAILS, ESTIMATED REHAB
COST, CAPITAL COST
RISK ASSESSMENT
ANALYTICAL TOOLS
FINANCIAL TOOLS
ANALYTICAL RESULTS
[BSL, ABSL, MSL, IRR]
REHABILITATION BOQ
BILL OF QUANTITIES
ENHANCE RESILIENCE BOQ
RISK AND VULNERABILITY
ANALYSIS
DEFINE CRITICAL BRIDGE AND
TRANSFER NON CRITICAL
BRIDGES FOR FUND OPTIMISATION
DEFINE CRITICAL BRIDGE AND
TRANSFER NON CRITICAL BRIDGES
FOR FUND OPTIMISATION
FUND OPTIMISATION
USING MCDM
DATA DRIVEN
DECISIONS
RISK INFORMED
PRIORITISATION
OPTIMISED FUND
ALLOCATION
RESILIENT & SUSTAINABLE
INFRASTRUCTURE
MAXIMISED SOCIO-ECONOMIC
BENEFITS

CHAPTER 01: PREAMBLE SCREEN

BRIDGE RESILIENCE SYSTEM

The system will yield best results and efficient working if the following flow of activities is adhered to.

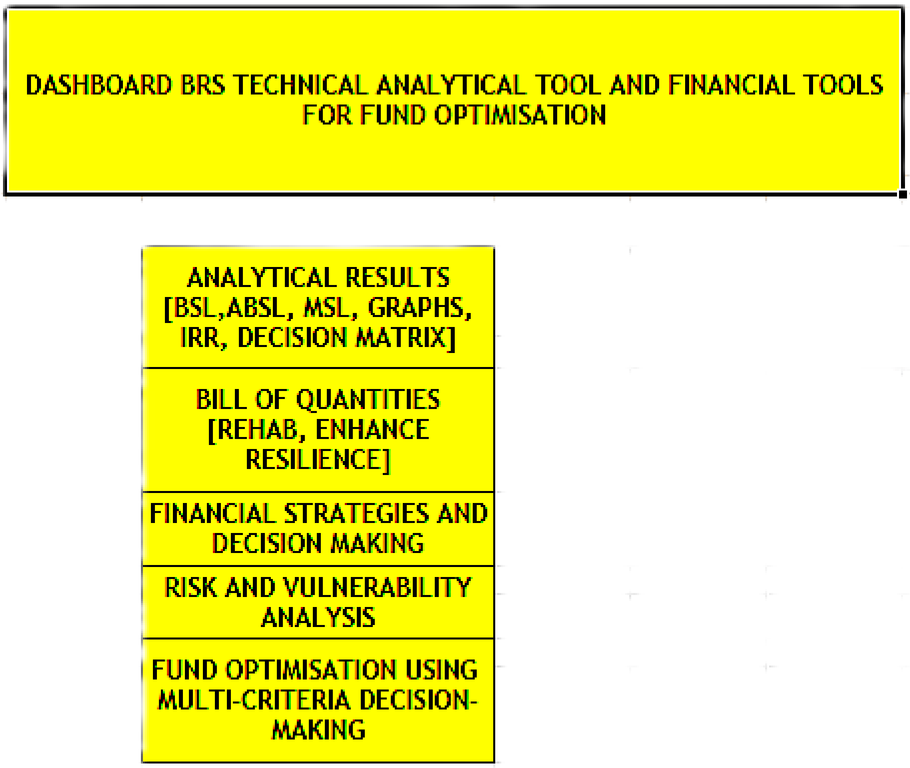


Once the User decides to add data for a new bridge to the system, it is essential that every step in the ADD DATA module is undertaken. The first screen that opens is the BRIDGE IDENTITY, LOCATION, GEOMETRY Screen. Only after submitting data for each of the fields, should the User move to the next screen by pressing the SYMPTOMS OF DISTRESS button at the Right hand bottom of the screen.
Similarly after submitting data for each of the fields in this screen the User can move to the next screen by using the button at the right hand bottom of the screen.

Once the user has submitted data for each of the screen and has the option to upload images. On uploading maximum of 6 images, the user can confirm the submission by using the Button SAVE AND ANALYSIS on the IMAGE UPLOAD Screen.

This will move the user to the original BRIDGE LIST and ADD BRIDGE Screen. The User can add new bridges in similar manner. Maximum of 25000 bridges data can be added. Higher the number of bridges, more time is taken for the analysis of results as it depends on the speed on internet, capacity of the hosting domain and the internal properties of the domain selected. For each bridge, 10 subsequent inspection data can be added.

On fully submitting the data for all the bridges, it is advisable to use the TECHNICAL ANALYTICAL TOOL & FINANCIAL TOOL FOR FUND OPTIMISATION.
While using these tools it is advisable to move from one screen to the next by using the functionalities in each screen in the order that the screen are presented. Once all the inputs and analysis for all stages is complete, then the user should use the FUND OPTIMISATION USING MULTI-CRITERIA DECISION-MAKING [MCDM]. The user is required to select 10 bridges for application of MCDM at one time and the process can be continued till all bridges are analysied.
In the FINANCIAL STRATEGY AND DECISION MAKING Screen, three types of results are presented, All Bridge suggested for Reconstruction, are excluded from the list of bridge available under MCDM. Similarity all bridges selected as CRUCIAL when using Risk and Vulnerability analysis are also excluded from the bridges available for MCDM.



Details for each of the screen and the procedure to submit the inputs are explained in subsequent chapters. Should any user have any queries, they can send their queries to sachidanand@ubmsresearchgroup.com or mayuri@ubmsresearchgroup.com

CHAPTER 02: WELCOME SCREEN FOR BRS

Welcome to Bridge Resilience System [BRS]

UBMS Research Group [URG] welcomes you to the Bridge Resilience System [BRS] — an advanced and integrated platform developed to support modern bridge resilience planning, structural evaluation, rehabilitation strategy, financial planning, and sustainable infrastructure management.

BRS is designed to empower bridge owners, infrastructure agencies, engineers, and decision-makers by transforming bridge-related data into a structured resilience-based management system that supports technical, functional, socio-economic, and financial decision-making.

The Bridge Resilience System provides a comprehensive framework for managing bridge identity, location, geometry, symptoms of distress, structural performance, cause identification, financial requirements, risk exposure, vulnerability analysis, and resilience enhancement strategies.

Unlike traditional bridge management approaches that primarily focus on condition monitoring, BRS advances the process by integrating resilience assessment, rehabilitation planning, risk evaluation, and multi-criteria decision-making into one unified platform. This enables users to identify bridge vulnerabilities, prioritize interventions, optimize rehabilitation investments, and improve long-term infrastructure sustainability.

BRS supports efficient and cost-effective bridge management by helping users:

- Assess bridge condition and resilience requirements
- Identify deterioration symptoms and probable causes
- Evaluate structural, functional, and socio-economic performance
- Estimate rehabilitation and capital investment needs
- Conduct risk and vulnerability analysis
- Generate analytical outputs for resilience planning
- Support sustainable and optimized decision-making

The Bridge Resilience System is developed to ensure that bridge infrastructure is managed not only for present operational safety but also for future resilience, sustainability, and economic continuity.

By combining engineering evaluation, financial analysis, risk assessment, and resilience planning, BRS delivers a modern bridge management framework that strengthens infrastructure performance, supports sustainable development, and shapes the future of bridge resilience.

CHAPTER 03: REGISTRATION PROCESS
[OPERATION OF BRIDGE RESILIENCE SYSTEM]

The Bridge Resilience System [BRS] registration screen is designed to register organizations, verify user identity, and provide secure system access through login credentials.

- Registration Screen
- Verification Screen
- Login Screen

Registration Screen:

The Registration Screen is used by organisations to create a new account in the Bridge Resilience System. Users must enter organization details, contact information, and subscription details to complete registration.

8. Name of Organisation
Enter the full official name of the organisation registering for access to the system. Access is granted only to orgnaisational entities.

9. Short Name Assigned as User Name
Enter a unique short name that will be used as the username for future login.

10. Mobile Number
Enter the active mobile number of the authorized user for OTP verification and communication.

11. Email Address
Enter a valid email address where the verification link will be sent. You can enter the login page only via this link for the first time post registration. Valid email address is the corporate email address. Gmail / Yahoo / Hotmail or similar email addresses are not permitted.

12. Country
Select the country from the drop-down list of available countries.

13. Start Date
The default date is the current registration date, with an option for the user to select or modify the date to a future date in the next week or so.

14. Period of Usage Selected
During the first usage; the TRIAL VERSION is auto-selected. The system can be used for a limited period of 10 days wherein the user is allowed to insert data for two new bridges and use all functionalities within BRS. This trial version allows the User to familiarize with the system. Acceptance to move ahead is considered as the Users acceptance of the functioning of the system.

On expiry of the 10 day trial version, the user is offered the subscription model for duration of 5 Years, or 10 Years. User has to select the duration of usage. On selection of the duration, the subscription plan available on that day is shown with payment link to complete the subscription process.

15. Payment Made Details
Enter the payment or transaction details related to the selected subscription period. On submission of the details, a link will be send to the registered email address to open the log in page.

16. Registration User Number
This is an auto-generated. User identification number in the format XXX1234MMYYYY. XXX represents the country code, 1234 represents the last four digits of the mobile number, MMYYYY represents the subscription end month and year.

17. Submit for OTP
Click this option to submit registration details and receive an OTP for verification. OTP is send to the mobile number entered in the registration screen. On submission, a link will be send to the registered email address to open the log in page.

Verification Screen:

The Verification Screen is used to confirm the registered user's identity through email verification and OTP authentication.

3. Verification Page Access
This page opens ONLY when the user clicks the verification link sent to the registered email address.

4. Submit OTP
An OTP is sent ONLY to the registered mobile number, which must be entered for successful verification.

5. User Name
The username displayed here is the short name assigned during registration.

6. Assigned Password

The system assigns a password based on the selected start date MMYYYY and end date period in mmyyyy format. SO the first time password is MMYYYYmmyyyy. This is auto-generated and can be changed by the user.

Login Screen:

The Login Screen allows verified users to securely access the Bridge Resilience System.

9. User Name

Enter the assigned username created during the registration process.

10. Password

Enter the password provided after successful verification.

11. Submit

Click Submit to log in and access the system.

CHAPTER 04: STANDARD PARAMETERS FOR BRS SCREEN

Standard Parameters are critical for evaluation of results within the Analytical tools of BRS. These parameters are essentially required to be updated annually. Unless these parameters are available for the year the user wishes to conduct analysis, the results will not be generated.

The Standard Parameters Screen is used to establish the technical, economic, operational, and regional risk parameters required for Bridge Resilience System [BRS] analysis. These parameters provide essential baseline values for bridge assessment, financial calculations, rehabilitation planning, and resilience evaluation. The parameters essentially required to be updated **ANNUALLY**.

This section provides the foundational parameters and baseline inputs required for bridge resilience evaluation. The parameters essentially required to be updated ANNUALLY.

The parameters required to be submitted include the following:

9. Year

Select the applicable analysis year from the dropdown list ranging from 2025 to 2050.

10. Country

The country field is automatically based on the country selected during the registration process.

11. Average Salary Per Week

Enter the average weekly salary applicable to the selected country or region for socio-economic and cost calculations.

12. Fuel Cost Per Liters

Enter fuel cost in multiples of INR 65 per liter to support transportation and economic analysis.

13. Average Number of Passengers Per Vehicle

The default value is set at 1.5 passengers per vehicle, with the flexibility to select values between 1 and 5.

14. Average Speed on the Network [Km / Hour]

Enter the average operational speed across the bridge network for transport and performance calculations.

15. Emission in [gm / Ltrs]

The default emission value is set at 2300 gm per litre, with an option to modify based on applicable standards.

16. Consumption of Fuel [Ltrs / Kms]

The default fuel consumption value is set at 10, with user input allowed up to a maximum value of 20.

17. Department Budget Available for Bridge Maintenance [IN MIL]

Enter the total maintenance budget available for bridge-related rehabilitation, repair, and resilience activities.

18. Conversion Ratio [Financial Cost to Economic Cost]

Select the conversion ratio from available options of 0.85, 0.90, or 0.95 for financial-to-economic cost assessment.

11. Risk Parameters Ratings as per Region

This section records hazard-specific regional risk ratings for Flooding, Cyclone, Landslide, and Earthquake.

A. North Region

Enter risk ratings applicable to northern regions for each hazard category.

B. East Region

Enter risk ratings applicable to eastern regions for each hazard category.

C. South Region

Enter risk ratings applicable to southern regions for each hazard category.

D. West Region

Enter risk ratings applicable to western regions for each hazard category.

E. Central Region

Enter risk ratings applicable to central regions for each hazard category.

CHAPTER 05: SELECTION OF CULVERT / BRIDGE MODULES & DASHBOARD SCREENS

SELECTION OF CULVERT OR BRIDGE SECTION

Subsequently the option to select either CULVERTS or BRIDGE is provided to the user.

CULVERTS options allows user to enter data for Culverts. List of Culverts for which data is available is exhibited. Addition of new culvert data is feasible from this screen. Once data is submitted, the Culvert appears in the list. Should one need to update the data after a fresh inspection, the same can be submitted and the data of previous inspection is erased and the new inspection data is visible. Only one inspection data is available for review.

BRIDGES options allows user to enter and analysis data for bridges. Maximum of 30,000 bridges data can be stored in the system for optimum speed of analysis. Maximum of 10 inspection cycles data can be saved and retrieved from the system.

Within the BRIDGES option two dashboards are available. The Dashboard Page serves as the primary navigation and operational control center of the Bridge Resilience System [BRS]. It provides users with access to all major modules required for bridge resilience data entry, analysis, assessment, and decision-making.

- **Two DASHBOARDS are provided under Bridge:**

    A) BRIDGE LISTING AND INSPECTION DATA

    B) TECHNICAL ANALYTICAL AND FINANCIAL TOOLS FOR FUND OPTIMISATION

In the various screens of the Dashboard are few parameters which we have provided a drop-down; with either the options to select of rating to be assigned by the user. There are explanations provided on the **"I"** button, where the user can click to read. Same details are provided in the Annexure A provided in this manual. The various screens in both the Dashboard with the parameters are described here under.

- **BRIDGE LISTING AND INSPECTION DATA**

1. Bridge Identity, Location, Geometry
This section captures essential bridge information including bridge name, identification details, geographical location, and structural geometry specifications.

2. Symptoms of Distress
This section records visible and measurable signs of bridge deterioration, damage, or distress affecting structural condition. Symptoms like Cracks, Delamination, Spalling, Distress near expansion joints, Vertical or horizontal movements are all recorded for

various locations/ component of the bridge. The severity and extent of the distress are also captured.

3. Ratings [Structural, Functional, Socio-Economic]

This section evaluates bridge performance across structural integrity, operational functionality, and socio-economic importance. Definition for each component rating is provided in Annexure A. User are cautioned to familiarize with the definitions before selecting the ratings.

4. Cause Identification - Ratings, Performance Rating

This section identifies possible causes of distress and assigns performance ratings based on observed conditions and assessment criteria.

5. Financial Details, Estimated Rehab Cost, Capital Cost

This section records financial inputs including rehabilitation cost estimates, repair budgets, and capital investment requirements.

6. Risk Assessment

This section analyzes potential risks associated with bridge condition, usage, and resilience factors.

7. Images Upload

This section allows users to upload bridge photographs, inspection visuals, and supporting image-based documentation.

TECHNICAL ANALYTICAL AND FINANCIAL TOOLS FOR FUND OPTIMISATION

8. Analytical Results [BSL, ABSL, MSL, Graphs, IRR, Decision Matrix]

This section presents analytical outputs, resilience indicators, graphical assessments, financial returns, and decision-support matrices. Results presented include the Balance Service Life [BSL], Absolute Balance Service Life {ABSL], Median Service Life [MSL], The principle cause of distress from Mechanical, Physical or Chemical process, Graph showing the MSL which enable user to understand the probable efficiency of rehabilitation intervention possible for this bridge. On the financial side the results include Internal Rate of Return [IRR] for tangible and intangible benefits.

9. Bill of Quantities [Rehab, Enhance Resilience]

This section provides quantity estimates for rehabilitation activities and resilience enhancement measures. Under this section the user will need to select from Rehabilitation or Enhancement of Resilience to compile the estimate for Rehabilitation or Resilience process. Estimation is totally User driven as the User will select the Principle of rehabilitation, the work methodology and then based on the selected work system submit the quantities, rates for various items. As EN1504

provides for 11 distress causes, the BOQ section provides the option to select either all 11 causes or the user can decide to select only few main causes for which the BOQ is compiled. Additionally the user can also select Non Structural rehabilitation works where the the items of works are User determined. The same applies for Expansion joint and Bearing rehabilitation works.
Under the Enhancement of Resilience part the User has the option to choose one of the three main cause of failure and then choose from the available Principle and work methods or decide to opt for Design and provide method.

10. Financial Strategies and Decision Making:

This section provides critical decision making to choose which of the bridges will need to be provided rehabilitation intervention immediately, or can be provided a planned rehabilitation intervention, or should be planned for reconstructed. Bridges assigned for reconstruction will not appear in the list of bridges in Multi-Criteria Decision-Making section.

11. Risk and Vulnerability Analysis

This section evaluates bridge vulnerability under various hazards, risks, and resilience scenarios. Based on the vulnerability index, the risk index is evaluated for four natural hazards [Flooding, Cyclone, Landslide, or Earthquake.] Bridges can be assigned to the list of Critical bridges which need to be provided with funds for rehabilitation and enhancement of resilience on the topmost priority. Such critical bridges name are deleted from the list of bridges in the Multi-Criteria Decision-Making section.

12. Multi-Criteria Decision-Making

This section provides financial decision-making by comparing multiple technical, financial, socio-economic and resilience criteria. Bridges not assigned to reconstruction in Financial Strategies and Decision Making section and not assigned to the Critical bridge list in the Risk and Vulnerability Analysis section will appear in this section. Such bridges will then be provided a priority for fund allocation.

CHAPTER 06: SCREEN - BRIDGE LISTING AND INSPECTION DATA

A] SCREEN --- BRIDGE IDENTITY, LOCATION, AND GEOMETRY

The Bridge Identity, Location, and Geometry Screen is used to capture the complete identification, geospatial, structural, and physical characteristics of the bridge. This section establishes the bridge's unique identity and provides essential baseline data for resilience analysis, inspection, and performance evaluation.

- **Code of Region**

Select the regional or state code from the drop-down list based on the country selected during registration. For India, this includes the applicable Indian state code.

- **Type of Road**

Select the road classification from the drop-down options such as NH, EX, SH, DR, CR, or RR.

- **Road Number**

Enter the assigned road number or route reference associated with the bridge location. The format assigned for this is NNNAA. Example is 048OA indicating 048A as the highway number.

- **Bridge Identity Number**

This field is auto-generated by combining the state code, road type, road number, and assigned bridge number to create a unique bridge identification reference. Typically the Bridge Identity number is in the format: MHNH048OAB25000 indicating that the bridge is located in India and the state of Maharashtra, lies on National Highway number 48A and the Bridge is at 25000 number in the database.

- **Bridge Name if Any**

Enter the official bridge name if one exists.

- **Geospatial Location**

Enter the exact geographical location details of the bridge for mapping and location reference.

a) Latitude

Enter the latitude coordinate of the bridge location.

b) Longitude

Enter the longitude coordinate of the bridge location.

- **Length of Bridge**

Enter the total overall length of the bridge structure. Format assigned is XXXX so if the bridge is 90 meters long the input is 0090; if the bridge is 670 meters long the input is 0670 and if the bridge is 1250 meters long the input is 1250

- **Number of Spans**

Enter the total number of spans forming the bridge. Format is XXX. Example if there are 7 spans the input is 007; if there are 25 spans the input is 025; and if there are 120 spans the input is 120

- **Max Span Length**

Enter the maximum span length among all spans within the bridge. Format is XXX. Example if the max span length is 7 the input is 007; if the max span length is 25 the input is 025; and if the max span length is 120 the input is 120

- **Number of Traffic Lanes**

Enter the total number of traffic lanes supported by the bridge. The format is XX.

- **Age of Bridge**

Enter the age of the bridge in years from the year of construction or commissioning.

- **Load Capacity**

Select the applicable load capacity classification from the drop-down options. Refer Annexure A for the same. The user is required to be conversant with the classification nomenclature used to define the Load Capacity.

- **Waterway Curvature**

Select the waterway curvature classification from the drop-down options as applicable. Refer Annexure A for the same.

- **Elevation of Bridge AMSL**

Select or enter the bridge elevation above mean sea level. Refer Annexure A for the same.

- **Type of Foundation**

Enter the structural foundation type supporting the bridge.

- **Shape of Pier**

Select the pier shape from the dropdown options based on structural design. Refer Annexure A for the same.

- **Pier Height in Meters**

Enter the vertical height of the pier structure.

- **Pier Width / Diameter in Meter**

Enter the width or diameter of the pier depending on pier shape.

- **Number of Girders**

Enter the total number of girders used in the bridge structure.

- **Secondary Rebar Diameter in Substructure**

Enter the diameter of secondary reinforcement bars used in the substructure. In case of non availability of correct information, the user is requested to input 18mm as the diameter

- **Depth of Deck**

Enter the structural depth of the bridge deck.

- **Depth of Superstructure [Girder / Beam]**

Enter the depth of the superstructure components including girders or beams.

- **Type of Bearing**

Enter the bearing type used in the bridge structure.

- **Percentage of Reinforcement in Superstructure**

Enter the reinforcement percentage applicable to the superstructure. In case of non availability of correct information, the user is requested to input percentage between 1 to 4 depending on the location of the bridge.

- **Percentage of Reinforcement in Substructure**

Enter the reinforcement percentage applicable to the substructure. In case of non availability of correct information, the user is requested to input percentage between 1 to 4 depending on the location of the bridge.

- **Number of Bearings per Location**

Enter the total number of bearings installed at each structural location.

- **Depth of Pier [Above Average Water Line]**

Enter the pier depth above the average water level.

- **Number of Girders / Beams per Junction**

Enter the number of girders or beams provided at each junction.

- **Width of Girders**

Enter the width of girders used in the bridge structure.

- **Shape of Pier Drop-down Options**

The available pier shape classifications include Pier with

➢ Round End
➢ Pier with Pointed End

- Circular Pier
- Square Pier
- Rectangular Pier

Refer Annexure A for the same.

- **LOCATIONS DETAILS:**

For location details following set of questions are required to be submitted.

Sr. No.	Question	Response
1	Is the bridge located within 100 kms from the coastline?	YES / NO
2	Is the bridge located on higher altitude / mountains?	YES / NO
3	Does the bridge experience extreme weather conditions [above 40°C or below 0°C]?	YES / NO
4	Is the bridge located in non-saline water body?	YES / NO
5	Is the bridge located in saline water body?	YES / NO
6	Does the bridge experience tidal variations?	YES / NO
7	Is the bridge located in earthquake zone 5 or 6?	YES / NO
8	Is the bridge located in earthquake zone 3 or 4?	YES / NO

- PAST HISTORY OF REHABILITATION

Sr. No.	Question	Response
1	Has the bridge undergone structural rehabilitation or retrofitting?	YES / NO
2	Has the bridge undergone surface cover rehabilitation?	YES / NO
3	Has the bridge undergone rehabilitation for corrosion distress?	YES / NO
4	Does the bridge experience fatigue due to increased traffic movement?	YES / NO

B] SCREEN --- SYMPTOMS OF DISTRESS

This section / screen needs the User to fill out the symptom details for various types of symptoms. Such symptoms consists of cracks in concrete [vertical, horizontal, diagonal, crazing/irregular cracks], delamination details, spalling details, distress near expansion joint details, concrete disintegration details, distress in bearing pad details, misalignment of bridge structure details, and any other observed visible distress symptoms affecting the bridge components.

For each symptom, record the location or type of distress, severity, and symptom rating based on observed condition. Location are as per components and not as per elements. So Users are advised to provide an overall view of the severity of distress and accordingly symptoms ratings are to be given. Three distinct ratings are provided in options [namely Low, Moderate, Severe].

Ensure that distress information is carefully captured for deck, superstructure, substructure, and foundation components wherever applicable.

NOTE: When there is no distress observed for a particular symptom, ensure “NA” is entered under Severity. Symptom Rating and Location/Type of Distress can be left blank where distress is absent and “NA” has been assigned to the Symptom.

C] SCREEN --- RATINGS [STRUCTURAL, FUNCTIONAL, SOCIO-ECONOMIC]

Bridge assessment is broadly divided into three major categories to evaluate the bridge’s physical condition, operational efficiency, and socio-economic significance. These categories help determine maintenance priority, rehabilitation needs, and overall bridge importance. User is requested to Refer Annexure A for definitions of ratings and the way they are classified from 1 to 5. Each rating definition is specific for which is sought. So do not generalize the ratings.

A. Structural Ratings

Structural ratings assess the physical and structural health of the bridge components to ensure safety, stability, and durability.

1. Deck

Refers to the roadway/slab surface where vehicles and pedestrians travel.
Includes wearing surface, cracks, potholes, delamination, drainage, and riding quality.
Evaluates serviceability and surface condition.

2. Superstructure

Superstructure is considered to be between the bearings and deck slab that supports the slab and traffic load. Includes girders, beams, trusses, slabs, diaphragms, and load-carrying members. Assign ratings by assessing cracks, corrosion, deformation, fatigue, and load transfer efficiency.

3. Substructure

Substructure is considered to be below the Superstructure and above the foundation cap/ foundation elements. It Supports the superstructure and transfers load to foundation. Includes piers, abutments, wing walls, and retaining structures.
Assign ratings by assessing based on settlement, cracking, scour effects, erosion, and stability.

4. Foundation

Lowest load-transferring component below ground/water. It Includes footings, piles, pile caps, wells, or caissons. Assign ratings by assessing by assessing scour, settlement, undermining, and bearing capacity.

B. Functional Ratings

Functional ratings assess whether the bridge adequately serves current transportation demands and geometric standards.

1. Deck Geometry [Lane Width]

Measures carriageway width and traffic accommodation. Evaluates adequacy for vehicle movement, lane safety, and future traffic needs. Narrow decks may reduce functionality and safety.

2. Vertical Clearance

Available height under/over the bridge for vehicles, rail, or waterways. Ensures safe passage for oversized vehicles or navigation. Insufficient clearance can restrict transport operations.

3. Waterway Adequacy

Assesses hydraulic capacity beneath the bridge. Evaluates flood passage, overtopping risk, and scour potential. Important for river/stream crossings.

4. Average Daily Traffic [ADT]

Represents traffic volume using the bridge daily. Indicates bridge importance, usage intensity, and demand. Higher ADT generally means higher functional significance.

C. Socio-Economic Ratings

Socio-economic ratings evaluate the broader community, economic, and environmental impact of the bridge.

1. Social Importance

Importance of the bridge for connectivity of communities, schools, hospitals, and emergency access. Determines public dependency.

2. Economic Growth

Measures contribution to trade, commerce, industry, and regional development. Important for bridges connecting markets, industrial zones, or economic corridors.

3. Alternate Route

Availability and practicality of alternate crossing options. Longer detours increase bridge importance.

4. Environmental Impact

Evaluates ecological consequences of bridge condition or failure. Includes effects on water flow, habitat, pollution, and surrounding environment.

D] SCREEN --- CAUSE MATRIX

This section helps identify the primary causes of deterioration, understand environmental or operational stressors, and support maintenance or rehabilitation decisions based on observed distress patterns. Refer Annexure A for definitions of ratings and the way they are classified from 1 to 5. Each rating definition is specific for which is sought. So do not generalize the ratings.

1. IMPACT
Used to identify damage caused by collision, sudden external force, vehicular strike, floating debris, or accidental loading that directly affects structural elements.

2. ABRASION
Refers to surface wear due to repeated friction, traffic action, flowing particles, or mechanical rubbing that gradually removes protective or structural material.

3. EROSION
Represents gradual loss of supporting material, soil, or surface due to water flow, wind, or environmental action that weakens surrounding stability.

4. OVERLOAD
Indicates structural stress caused when applied loads exceed intended design capacity, often due to increased traffic, heavy vehicles, or unauthorized usage.

5. FATIGUE
Describes progressive weakening caused by repeated cyclic loading over time, leading to cracks, reduced durability, or long-term performance loss.

6. TEMPERATURE
Captures deterioration caused by thermal expansion, contraction, freeze-thaw cycles, or extreme climatic variation affecting materials and joints.

7. SHRINKAGE
Relates to volume reduction in materials, especially concrete, due to moisture loss or curing effects, which may lead to cracking or internal stress.

8. SETTLEMENT
Represents vertical or differential movement of foundations or supports due to soil movement, compaction, or inadequate bearing conditions.

9. CHLORIDE INGRESS
Indicates penetration of chlorides, commonly from saline environments or de-icing salts, which can accelerate corrosion of embedded steel.

10. SULPHATE INGRESS
Refers to chemical attack from sulphates in soil or water that can degrade concrete durability and compromise material integrity.

11. CARBONATION
Describes the process where carbon dioxide penetrates concrete and reduces alkalinity, increasing the risk of reinforcement corrosion.

12. ALKALI-AGGREGATE INTERACTION
Represents internal chemical reactions between alkalis and reactive aggregates that may cause expansion, cracking, or long-term material distress.

SHORT TERM SHM [STRUCTURAL HEALTH MONITORING]
Used to determine whether temporary monitoring has been conducted to evaluate immediate structural performance, distress progression, or abnormal behavior.

SHM CHANGE RATING
Indicates whether monitored performance variation remains within acceptable limits or shows significant deterioration requiring further intervention.

E] SCREEN --- FINANCIAL DATA

The Financial Details, Estimated Rehabilitation Cost, and Capital Cost are required to be provided in this screen. These values are used to capture the financial history, construction investment, maintenance expenditure, and rehabilitation cost requirements of the bridge. This section supports financial planning, lifecycle costing, and resilience-based investment analysis.

1. Construction Cost in Million

The construction cost is calculated based on bridge length using the formula: *200 multiplied by the total bridge length in meters, divided by 1000. User can be provided the option to alter this figure of 200 mil which is considered the constant cost per running meter for typical bridge in India.*

2. Year the Construction Started

Enter the year in which the bridge construction officially commenced.

3. Year the Construction Completed

Enter the year in which the bridge construction was completed and operational.

4. Number of Years for Construction

This value is calculated as the difference between the construction completion year and the construction start year.

5. Annual Maintenance Cost in Terms of Percent of Capital Cost of Bridge

Select the annual maintenance cost percentage from the drop-down options of percent of the bridge's capital cost: 0.5, 1.0, 1.5, 2.0

6. Periodic Maintenance Cost in Terms of Percent of Capital Cost

Select the periodic maintenance cost percentage from the drop-down options of 2, 3, or 4 percent of the bridge's capital cost.

7. Estimation of Rehabilitation Cost Based on Latest Inspection in Million

Enter the estimated rehabilitation cost based on the most recent bridge inspection findings and required intervention measures.

F] SCREEN --- RISK ASSESSMENT

The Risk Assessment Screen is used to evaluate bridge vulnerability based on geographical location, hazard exposure, historical disaster events, and regional risk classification. This module supports resilience planning by identifying the level of exposure to major natural hazards and their potential impact on bridge safety and performance.

Zone Based on Bridge Location

The bridge risk zone is automatically assigned based on the state selected in the Bridge Identity Screen using predefined regional and seismic classifications.

Hazard

This section evaluates the bridge against four major hazard categories: Flooding, Cyclone, Landslide, and Earthquake.

Rating Assigned

Assign a hazard rating for each hazard category based on regional vulnerability, historical data, and bridge exposure.

1. What Was the Duration of the Last Recorded Event?

Enter the duration of the most recent hazard event affecting the bridge location.

2. What Was the Average Intensity?

Enter the average severity or intensity level of the recorded hazard event.

3. In Which Year Was the Last Known Severe Event Occurrence?

Enter the year of the most recent severe hazard event in the bridge region.

4. What Percentage of Bridges Were Damaged Extensively?

Enter the percentage of bridges within the affected region that experienced major damage during the event.

5. What Percentage of Bridges Failed?

Enter the percentage of bridges that completely failed during the hazard event.

6. Average Number of Events That Happened in the Immediate Preceding 10 Years

Enter the average frequency of hazard occurrences over the last ten years.

7. In the Last Three Years When Did the Event Occur?

Enter the timing or year[s] of hazard occurrence during the last three-year period.

REGIONAL RISK CLASSIFICATION

(1) Northern Region

Includes Jammu & Kashmir, Himachal Pradesh, Uttarakhand, Punjab, Haryana, Delhi, Uttar Pradesh, and Bihar. This region is classified as High to Very High Risk with Seismic Zone IV and V.

(2) Eastern Region

Includes West Bengal, Sikkim, Assam, Arunachal Pradesh, Meghalaya, Nagaland, Manipur, Mizoram, and Tripura. This region is classified as Moderate to High Risk with Seismic Zone III and IV.

(3) Southern Region

Includes Tamil Nadu, Kerala, Karnataka, Andhra Pradesh, Telangana, and Odisha. This region is generally classified as Moderate Risk with Seismic Zone II and III.

(4) Western Region

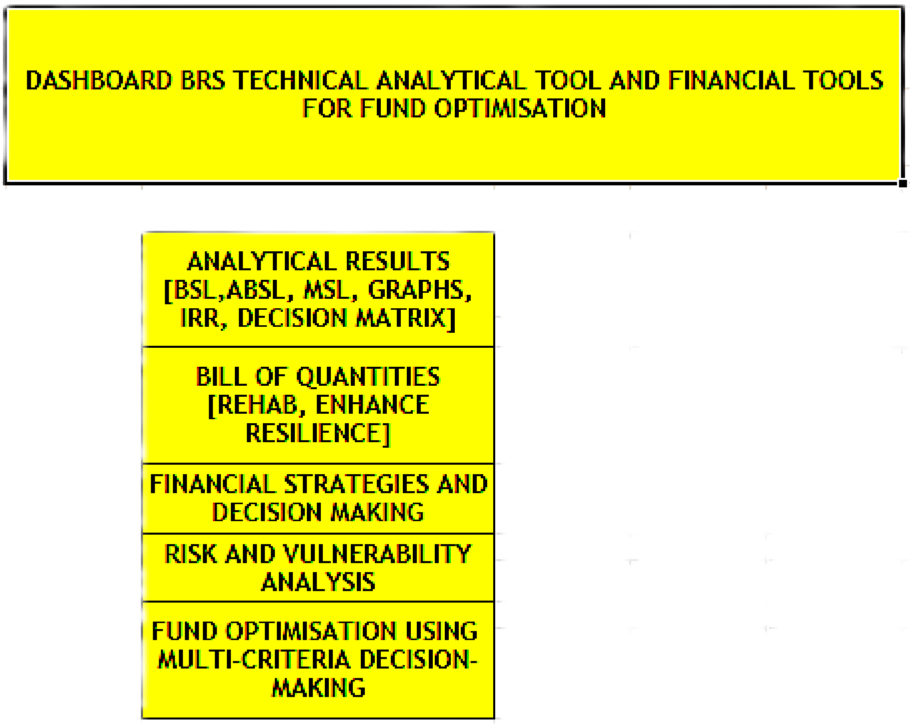
Includes Gujarat, Maharashtra, Goa, and Rajasthan. This region is generally classified as Moderate Risk with Seismic Zone II and III.

(5) Central Region

Includes Madhya Pradesh, Chhattisgarh, and Jharkhand. This region is generally classified as Moderate Risk with Seismic Zone II and III.

CHAPTER 07 - TECHNICAL ANALYTICS TOOL AND FINANCIAL TOOL FOR FUND OPTIMISATION DASHBOARD

This Dashboard allows the user to achieve results that are critical to final step of fund optimisation using the Multi-Criteria Decision-Making tool. This enables the user to determine which of the bridges are critical and need to provided with rehabilitation intervention or which need to enhance resilience. Such critical bridges are first attend to and then fund optimisation technique is applied to remaining bridges using the MCDM module.



A] SCREEN --- ANALYTICAL RESULTS [BSL, ABSL, MSL, GRAPHS, IRR,]

The Analytical results screen provides aggregation of results from technical analytical tools of BRS. The results that are evaluated are as under

1. Balance Service Life [BSL]: This indicates the effective period available within which it is still feasible and economically viable to undertake rehabilitation or repair and maintain the bridge structure. It indicates the period when the bridge can carry the intended load safely. Balance Service life is different from the difference of Design Service life and age of the bridge. This difference is reduced by the deterioration process caused due to distress.
2. Absolute Balance Service Life [ABSL]: indicates the period available to initiate rehabilitation intervention process without compromising the safety of bridge structure.

3. Median Service Life [MSL]: is specific and related to the process of deterioration [Mechanical, Physical or Chemical] Depending on the deterioration process affecting the Bridge, the time period available to implement efficient rehabilitation is the Median Service Life. If the age of the bridge is higher than the Median Service life, the efficiency of rehabilitation will be below 50%. So it is critical to know the Median Service life. The graph of MSL is unique for each process.
4. Internal Rate of Return [IRR] is evaluated for two scenarios. Tangible IRR which is the direct benefit accrued to the region due to the bridge. Examples of factors contributing to Tangible IRR being Saving in Vehicle Operation Cost, Saving in Vehicle Operating Time. The second IRR evaluated is the Non-Tangible IRR or indirect Benefit accrued to the region due to the bridge. Example of this being the socio-economic benefit, economic development benefit.

Based on the Cause of distress affecting the bridge, the prinicpal process of deterioration is decided. This process determines the MSL. For the deterioration, BSL and ABSL are evaluated and presented. BSL and ABSL also evaluated when the bridge is subjected to Short term Structural Health Monitoring [SHM]. This is critical for bridges which are ageing.

B] SCREEN --- BILL OF QUANTITY [REHABILITATION AND ENHANCE RESILIENCE]

The Bill of Quantity [BOQ] Screen is used to prepare, estimate, and summarize the quantities and financial requirements associated with bridge rehabilitation, resilience enhancement, repair works, and maintenance activities. This module supports cost planning, budgeting, and prioritization of bridge intervention activities. The division is based on interventions. Rehabilitation intervention and Enhancement of Resilience.

1] REHABILITATION BOQ

The Rehabilitation BOQ module enables the user to define work items, quantities, unit rates, and total estimated cost associated with rehabilitation measures required for improving bridge safety, durability, and resilience performance. The structural interventions are driven by EN1504, meaning that as per the defined Cause of distress, the user has the option to select the Principle of rehabilitation and based on the Principle, the user can select the work methodology. 11 Causes within the Cause matrix covers the structural rehabilitation. For Non structural items, the user can define the methodology of repairs. For Bearing and expansion joint repairs, the user has the option to select “Design the system of repair and implement” offering total flexibility to decide the methodology.

Bridge Identification Details

The bridge identification section displays the bridge details associated with the BOQ preparation, ensuring that all rehabilitation quantities and financial estimates are linked to the correct bridge asset.

Once the bridge is selected, the user has to prepare the Pre Rehabilitation items of works which include common items that are essential prior to any rehabilitation work. Generally the quantities of all the items need to cover the whole Bridge underbelly surface [Approach platform]. For quantities related to concrete rehabilitation the user will need the quantities from the field inspections. For quality control items, safety items, inspection to determine the correct quantities; the user will need to keep handy the Lump sum rate applied once. Similarity for post rehabilitation items the Lump sum rates for total coating the bridge surface, quality check post rehabilitation and concrete mix design are needed.

Post submitting the Pre and Post rehabilitation items of work details, the User can select the Cause using the Button “ADD NEW CAUSE / PRINCIPLE / METHOD SELECTION.” User will need to ensure to select the **LEVEL OF SEVERITY** for the Causes of distress button to be activated.

The user has the liberty to decide how many Causes of distress need rehabilitation. Rehabilitation quantities for each of the selected Cause of distress are required. Once the User selects the Cause, user has the option to select the Principle of rehabilitation and based on the Principle, the user can select the work methodology. Based on the methodology selected, the Items of works appear and the user will need to submit the details for all the items of work. Users are advised to decide and select all the Causes of distress in need of rehabilitation in one go, else the user will have to scroll up and select the Cause every time.

On completion of submitting the details in the Items of work, the User can then decide the Non structural items of work, Bearing and Expansion joints items of work.

Description of Work Item

The description of the rehabilitation, repair, strengthening, maintenance, or resilience enhancement activity proposed for the bridge are decided based on the Method selected.

Unit of Measurement

Similarly the unit applicable is predefined for the work item such as meter, square meter, cubic meter, kilogram, number, or lump sum.

Quantity

The User will need to enter the estimated quantity required for the specified work item based on inspection findings and rehabilitation scope. Caution is advised for the User to be conversant with the EN1504 methodology and the process to estimate the quantities of work. The Software will eventually calculate the total cost based on the input quantities. The quantities provided by the User are modified based on the Severity of Distress selected. The Chart is available to appraise the user regarding the modified quantities that will be applied.

Unit Rate

The User will need to enter the rate per unit for the selected work activity. The rate should be based on approved schedules, market values, or project-specific estimates.

Total Cost

The total cost is calculated automatically by multiplying the quantity with the unit rate for each work item.

Once data is submitted for each Cause of distress, Non Structural Items of work, Bearing and Expansion joint repairs, the User should scrutinize the entire Bill of Quantities screen properly for any errors in submission. Once he ascertains the correctness, then and then only should the User use the SUBMIT BOQ button. Once this is used, the option to modify the BOQ does not exist.

Submit BOQ

The Submit BOQ option saves the Bill of Quantity details and links the information with the bridge analytics and financial evaluation modules.

Reset Option

Prior to SUBMIT BOQ, the user can utilize the Reset option clears all entered values and restores the screen to its default input condition.

The BOQ module plays an important role in estimating rehabilitation expenditure, evaluating maintenance priorities, supporting lifecycle cost analysis, and assisting decision-makers in allocating available bridge maintenance funds efficiently and systematically.

2] RESILIENCE ENHANCEMENT BOQ

The Resilience Enhancement Screen is used to evaluate, plan, and estimate resilience improvement measures for bridges based on bridge condition, distress severity, structural vulnerability, and possible modes of failure. This module supports resilience-based rehabilitation planning and cost estimation for improving bridge safety, durability, and long-term performance.

BRIDGE INFORMATION

Name of the Bridge

Select the bridge name from the available bridge inventory list. The selected bridge will be linked to the resilience enhancement assessment.

Date

Select the date on which the resilience enhancement assessment or inspection is carried out.

Latitude

Enter the geographical latitude coordinate of the bridge location for accurate spatial identification.

Longitude

Enter the geographical longitude coordinate of the bridge location for accurate mapping and analysis.

Length

Enter the total length of the bridge in meters.

No. of Lanes

Enter the total number of traffic lanes available on the bridge.

Severity of Distress

Select the severity level of the observed bridge distress based on inspection findings and structural condition.

Engineer / Inspector

Enter the name of the engineer or inspector responsible for carrying out the bridge assessment.

RESILIENCE ENHANCEMENT

The Resilience Enhancement section is used to identify possible structural vulnerabilities, define modes of failure, and recommend resilience improvement measures for the bridge.

Add Mode of Failure

The “Add Mode of Failure” option allows the user to enter possible failure mechanisms affecting the bridge, such as foundation instability, corrosion, deck deterioration, bearing failure, flooding impact, seismic vulnerability, or structural distress.

Resilience Improvement Measures

Based on the identified failure modes, the system enables entry of rehabilitation measures, strengthening techniques, protection systems, and resilience enhancement solutions.

Total Resilience Cost

The system automatically calculates the total estimated resilience enhancement cost based on the entered rehabilitation and resilience improvement activities.

Reset

The Reset option clears all entered information and restores the screen to its default values.

Submit BOQ

The Submit BOQ option saves the resilience enhancement details and associated financial estimates into the Bill of Quantity and analytical modules.

The Resilience Enhancement module plays an important role in identifying bridge vulnerabilities, improving structural resilience, minimizing future risks, supporting lifecycle performance, and ensuring sustainable bridge asset management under varying hazard and operational conditions.

C] SCREEN --- FINANCIAL STRATEGY AND DECISION MAKING

The section for Financial Strategy and Decision Making enables User to evaluate the “Efficiency of Rehabilitation” [EC], “Frequency of Rehabilitation” [FR] and “Rehabilitation Avoidance Factor” [AF] for the bridge. These values are critical in the overall decision making when multiple bridges are in need for funds. This evaluation is based on the Age of the Bridge, the evaluated Balance Service life, Absolute Balance Service life, the Median Service life and the main process [Mechanical, Physical or Chemical] for deterioration / distress.

The section allows the User to Select the bridge for which this evaluation is to be done and then enables the User to submit the results to the Listing of Bridges.

Under Listing the User can view all the Financial Strategy evaluation at one place and based on the results can firm up the list of bridges which are required to be provided with “Rehabilitation on Immediate basis” or “Rehabilitation is required” or the “Bridge to be Reconstruction”.

The User can compile the list of Bridges that he has to pick on priority during the MCDM process.

D] SCREEN --- RISK AND VULNERABILITY ANALYSIS

The Risk and Vulnerability Analysis [RVA] Module is used to evaluate bridge vulnerability, hazard exposure, structural criticality, and operational risk based on multiple resilience and performance parameters. The module supports resilience-based bridge management, hazard prioritization, and decision-making for rehabilitation and emergency response planning.

The RVA system integrates hazard exposure analysis, structural condition assessment, socio-economic importance, functionality evaluation, and relief and rescue criticality into a unified risk assessment framework.

CREATE RVA

The Create RVA option allows the user to initiate a new Risk and Vulnerability Analysis for a selected bridge.

The module evaluates the bridge using hazard exposure data, bridge condition ratings, socio-economic importance, functional requirements, and resilience parameters.

RVA REPORT

The RVA Report generates a detailed analytical report containing computed risk values, hazard scores, vulnerability indices, and bridge criticality classification.

RVA DASHBOARD

The RVA Dashboard provides a summary of all bridges undergoing Risk and Vulnerability Analysis along with their current status, hazard classification, and risk indices.

Total Bridges

Displays the total number of bridges included in the RVA management system.

RVA Completed

Displays the number of bridges for which the RVA process has been completed successfully.

Critical Bridges

Displays the number of bridges identified as critical based on risk and vulnerability assessment.

Pending RVA

Displays the number of bridges for which RVA analysis is still pending.

RISK AND VULNERABILITY INPUTS

Does the User Want to Do Risk & Vulnerability Analysis?

This option enables or disables the RVA assessment process for the selected bridge.

In Which Zone Does the Bridge Lie

Select the regional hazard zone corresponding to the bridge location.

HAZARD PARAMETERS

The RVA module evaluates bridge vulnerability against multiple hazard categories.

1. **Flooding Hazard Exposure**
   Evaluates the bridge vulnerability to flooding events and hydraulic impacts.
2. **Cyclone Hazard Exposure**
   Evaluates bridge exposure to cyclone-induced wind and environmental effects.
3. **Landslide Hazard Exposure**
   Evaluates the risk associated with slope instability and landslide activity near the bridge.
4. **Earthquake Hazard Exposure**
   Evaluates bridge vulnerability to seismic activity and earthquake loading.

COMPUTED RISK VALUES

5. **Average Rating**
   Represents the average rating assigned to the hazard category.
6. **Fraction Assignment**

Represents the assigned weight or fraction used in risk calculations.

7. **Weighted RVA Score**

   Displays the weighted vulnerability score for the selected hazard.

8. **Risk Score**

   Displays the calculated risk value for the bridge based on the hazard analysis.

9. **Composite Risk Scoring**

   Displays the combined risk score obtained after integrating all hazard and vulnerability parameters.

10. **Risk Index**

    Represents the final normalized risk index value used for bridge prioritization and decision-making.

TRANSFER TO MCDM

The RVA module transfers the calculated hazard risk indices into the Multi-Criteria Decision-Making [MCDM] module for advanced prioritization, fund optimization, and rehabilitation planning.

CRITICAL BRIDGE CLASSIFICATION

11. **Critical**

    Bridges identified with high vulnerability, high hazard exposure, or significant operational importance are classified as Critical Bridges.

12. **Non-Critical**

    Bridges with lower vulnerability and manageable risk levels are classified as Non-Critical Bridges.

SUBMIT RVA ANALYSIS

The Submit RVA Analysis option saves the completed RVA assessment and transfers the analytical results into the resilience, financial, and MCDM modules for further decision-making and prioritization.

The RVA module plays a critical role in bridge resilience planning, disaster preparedness, hazard mitigation, infrastructure sustainability, and optimized bridge asset management.

E] SCREEN --- FUND OPTIMISATION USING MULTI-CRITERIA DECISION-MAKING

Introduction

Bridge management ensures safety, functionality, and sustainability, integrating engineering principles, economic constraints, environmental impacts, and social considerations. Multi-Criteria Decision Making (MCDM) enhances decision-making by evaluating multiple criteria, including safety, cost, environmental impact, and user convenience, thus providing a comprehensive approach. MCDM methodologies, such as the Simple Multi Attribute Rating Technique [SMART], and Analytic Hierarchy Process (AHP) explored to optimize resource allocation in bridge management. Fund allocation in bridge management aims to ensure efficient maintenance, upgrades, and resilience across global regions through Multi-Criteria Analysis (MCA). Criteria prioritization includes safety, structural integrity, operational efficiency, resilience against natural disasters, and socio-economic impacts like economic benefits and community advantages.

Image Credit 03: istockphoto frantic00 (Destroyed road bridge)

Assessing distress levels and service life balance of bridges across different regions guide's maintenance prioritization, and optimizing fund utilization. Enhancing resilience in bridges on critical routes ensures operational continuity during disruptions, minimizing economic impact and long-term repair costs. Evaluating socio-economic impacts justifies investments in bridge projects that offer significant returns, fostering sustainable development. Assessing financial viability through Internal Rate of Return (IRR) analysis helps prioritize economically feasible bridge projects, minimizing financial risks while maximizing returns. Ensuring the functional adequacy of bridges involves optimizing traffic flow and safety standards to enhance operational efficiency, crucial for economic growth. Assessing vulnerability to natural hazards mitigates risks by strengthening bridge resilience, and minimizing downtime and repair costs during disasters.

Transition from digitized bridge management based on identification of symptoms of distress to identification of cause of distress happened before 2015. Subsequently, the need to integrate various innovative technologies within bridge management gained importance. Post COVID, need to have sound financial due diligence was felt early. Bridge Management research responded with the integration of Life Cycle Cost Analysis [LCCA] within Bridge Management. For evaluating, direct tangible benefits that accrued due to existence of the bridge to the region, various techniques identified. Intangible or indirect benefits also evaluated. With the culmination of research regarding deterioration process, identification of various stages in deterioration propagation happened [EN1504]. Post publication of EN1504, various protocols emerged to correlate the distress in bridge components with the cause of distress.

Bridges, as vital components of infrastructure, and play a critical role in connecting communities and facilitating transportation. Bridges like all structures are prone to deterioration. Deterioration can originate from abuse in any form. Overloading, aging, fatigue, action of natural forces, temperature variations are few examples of different factors contributing to deterioration process. In recent years, natural hazards presents a very challenging situation for bridges. In recent years, natural hazard's frequencies and severity are becoming difficult to predict. These natural hazard's forces pose a challenge to the stability of the bridges. Symptoms often serve as early indicators of underlying structural issues. Cracks, rust, and deformation are among the visible signs that demand attention. Understanding how these symptoms manifest and evolve over time provides valuable insights into the broader challenges faced by bridges in the presence of natural hazards. To comprehend the impact of natural hazards on the deterioration process, one must first recognize the subtle yet telling symptoms exhibited by existing bridges.

All bridge structures have a very predominant deterioration process. Until late seventies – early eighties, symptoms observed symbolized the start of deterioration process. Recent advances, confirm that symptoms are indicative of deterioration process only in the early ages of the bridge life period. Based on the Design Service Life [DSL] in the early age, below 20 percentage of DSL, symptoms are sufficient indicators of deterioration. Symptoms that are most pronounced include crazing, cracking (minor to severe), delamination, spalling, deformities, rust stains, and porosity.

Beyond 20 percentage of DSL, symptoms alone may not identify correctly the deterioration model. Various early age symptoms may help to identify the Principal Cause. There could be multiple causes, which manifest the entire deterioration model. EN1504 researched and published in Nineties; define three main processes that can result in deterioration in concrete. The defined deterioration processes are

- ❖ Mechanical process
- ❖ Physical process
- ❖ Chemical process

Further, 11 Causes form the subdivision of these three processes. These 11 causes entirely define the deterioration model of the concrete structures. Multiple causes can contribute towards the deterioration model. Most of the time initial symptoms manifest into one of the cause. This manifestation occurs as the age of the bridge structure advanced. When age of the bridge structure is beyond 20 percent of DSL, identification of cause is feasible. Identification of Cause helps the bridge inspection teams from the age between 20 to 60 percent of DSL.

Impact of aging in the bridge structure is pronounced when age of the bridge exceed 60 percent of DSL. Bridge inspection teams have then to rely on Short term monitoring of components of the bridge structure, which show persistent symptoms. Structural Health Monitoring [SHM] adopted for short duration [36 – 48 hours] and then repeated three to four times, at intervals of three to four months, reveal the decrement in performance. Past research in SHM have recognized that as deterioration progress, performance decreases.

The effect of repeated cyclic loading (overloaded at times), fatigue, and internal corrosion of embedded reinforcements all may not manifest to visible signs. Monitoring of such aging bridges is the only method to access the realistic data related to the deterioration model. The existence of distress in bridge structure begins from day one. Internal and external factors results in propagation of distress.

All existing bridges globally have this propagating distress. Every existing bridges are in varying stage of deterioration process. This degree of distress is dependent upon the age of bridge, geospatial location and exposure to environment.

Each natural hazard has a typical force configuration that acts on the bridge structure. Increased severity of the hazard magnifies this force configuration on the bridge. The impact of such forces on the bridge structure is critically dependent upon the stage of the deterioration model of the bridge structure. When one has to evaluate the consequence of natural hazards on existing bridges, it is critical to understand and have clarity on how the forces of natural hazards will act on pre-existing deterioration model. This makes it essential to model varying deterioration stages and impose the force of natural hazard on the bridge structure. Results of such a study, enabled research define the consequences of the hazard on the bridge structure.

The statistically proven four hazards analyzed majorly cause bridge collapse globally. Earthquake, Cyclone, Floods, and Landslides are the four hazards for which GABM provides analysis. Globally these four hazards have been the main reason for bridge collapse. Within these four hazards, the principal type of failure are -

- Substructure failure due to shear force.
- Superstructure overturning or toppling.
- Superstructure unseating and then toppling

All the above type of failure mechanism can cause a cascading failure to set in. A local failure in a single element has a potential to result in adjacent areas to fail. Such a cascading impact result in total collapse of a bridge. GABM evaluates the magnitude of force (due to natural hazards) essential to result in element failure under known level of pre-existing deterioration process.

Risk assessment Module: Enables evaluation of risk index for each of the four natural hazard. Hazards historical data generate the risk that bridge had due to the location.

Clubbing this data with the deterioration model of the bridge, analysis yields the Vulnerability index for the bridge for a particular hazard. Vulnerability index then enable evaluation of risk index for each hazard on the bridge.

Deterioration to Failure scenarios Module: Post occurrence of an event of known severity, the user can generate the probability of failure for each of the bridge structure for the forces generated. This module provides the response of the Deteriorated Bridge to occurrence of natural hazard. It helps defines severity limits for each hazard wherein the bridge can survive and remain functional. This information is crucial for the post occurrence rescue and relief operations success. The success of this operation depends on the time required to reach the hazard zone. Arrival of rescue teams within the golden hour avoids fatalities and saves human lives. The occurrence does not turn into a major calamity.

Bridge Resilience Module: This module helps the users to identify the safe route to reach the hazard zone from a known point of origin. The safe route is a route wherein most of the bridge show resilience and very high probability of survival post occurrence of the hazard.

The task of decision-making processes becomes complicated due to multiple criteria involved. Single criterion drove decision- making prior to emergence of risk assessment Module. Provision pf fund happened only for bridges with very severe distress. The need to move from mono criterion to multi-criteria process is essential. This makes introduction of Multi-Criteria Analysis essential within Bridge Management.

The following system evolved for application of MCDM to Bridge management.

Apply Simple Multi Attribute Rating Technique [SMART]

Road authorities or Road/ Highway Concessionaire corporate identity use Bridge Management. By default, such agencies are the decision-making authorities. The objective of optimal fund allocation now changes from being mono-criterion to multi-criteria[19,20]. Four alternatives / criteria now essential decide the priority of fund allocation. The criteria that now needs inclusion in decision-making protocol are:

- Distress in bridge
- Economic growth potential of the bridge
- Socio-economic importance of the bridge
- Vulnerability and risk to bridge from natural hazards needing enhanced Resilience in bridges.

This emergence of multi-criteria requires assigning importance to all four criteria based on their criticality. The assignment of values will need to be in a common scale. Financial costs would require a scale that provides information about the high cost or lower cost. Whereas the resilience of bridge would need to have scale that indicate need for enhancement. We assign value function additive model.

Since the users of Multi-Criteria Decision-making are varied, importance of criteria may vary. The first step would be for the user to rank the four criteria as per their importance. Incorporation of comparison between two criteria at one instance to evaluate which of the two is more important, then comparing the important criteria with the third criteria to decide which is more important and finally the comparison of the forth criteria with the selected important criteria. This simple comparison algorithm will help the user rank the criteria.

- Compare Criteria A with Criteria B; Select more important, Say Criteria B.
- Compare Criteria B with Criteria C; Select more important, Say Criteria B.
- Compare Criteria B with criteria D; Select more important, Say criteria D.

Rank first position; Say Criteria 1
Now using the remaining three criteria rank Criteria 2
Similarly evaluate Criteria 3.
The last remaining criteria ranked as Criteria 4.

To each of the ranked criteria the software assigns weights.

Criteria 1 assigned 0.35,
Criteria 2 assigned 0.3,
Criteria 3 assigned 0.2, and
Criteria 4 assigned 0.15

Next step entails assignment of score for each criterion as per value function scale. Most of the data essential for this definition is available within GABM. Proper definition of value function scale provided within the software. Scale used from 1 to 5

Scale value	**Description**
1	Best performance within the criteria
2	Very good performance
3	Good performance
4	Moderate performance
5	Worst performance within the criteria

Assignment of score for each criterion as per value function scale

For four criterion used within MCDM, the rating definitions are as under:

Structural status / Level of distress **Economic growth potential**

Scale value	Description
1	Structure is sound / minor distress observed. Avg. BSRN less than 2
2	Structure is stable / moderate distress observed locally. Avg. BSRN greater than 2 but less than 2.75
3	Structure shows extensive moderate distress. Avg. BSRN greater than 2.75 but less than 3.5
4	Structure shows extensive severe distress. Avg. BSRN greater than 3.5 but less than 4.0
5	Structure shows extensive very severe distress. Avg. BSRN greater than 4.0

SOCIO- ECONOMIC IMPACT

1	Non-Tangible IRR less than 15
2	Non-Tangible IRR greater than 15 but less than 20
3	Non-Tangible IRR greater than 20 but less than 23
4	Non-Tangible IRR greater than 23 but less than 25
5	Non-Tangible IRR greater than 25

Scale value	Description
1	Tangible IRR divided by Nontangible IRR less than 1.25
2	Tangible IRR divided by Non-tangible IRR greater than 1.25 but less than 1.5
3	Tangible IRR divided by Non-tangible IRR greater than 1.5 but less than 1.75
4	Tangible IRR divided by Non-tangible IRR greater than 1.75 but less than 2.0
5	Tangible IRR divided by Non-tangible IRR greater than 2.0

RISK ASSESSMENT

1	Combined Vulnerability index and Combined Risk index both less than 0.15
2	Combined Vulnerability index and Combined Risk index both greater than 0.15 but less than 0.2
3	Combined Vulnerability index and Combined Risk index both greater than 0.2 but less than 0.23
4	Combined Vulnerability index and Combined Risk index both greater than 0.23 but less than 0.27
5	Combined Vulnerability index and Combined Risk index both greater than 0.27

MCDM rating

The evaluation of combined score and weightage to the criteria done using the simple additive model. Simple weighted score technique deployed. Score assigned in that criterion multiplied by Weightage assigned to each criterion. The highest of the weighted score indicates the importance of the bridge for fund allocation under that criterion. Four criteria may yield different bridges. Accordingly, ranking assigned to the set of bridges for which MCDM is applied. Typical comparison of ranked bridges remedial intervention [RI] costs to the available budget of the department yields a set of bridges, for which RI provided.

Purpose of the Module

a) The MCDM Module aims to bridge the gap between engineering assessments and strategic financial planning. Specifically, the module is designed to:

b) Support Strategic Decision-Making: Provide a scientifically sound basis for selecting optimal maintenance interventions.

c) Enable Transparent Fund Allocation: Allow stakeholders to understand the rationale behind funding priorities.

d) Integrate Multi-Dimensional Factors: Incorporate technical, economic, risk-related, and socio-economic aspects into decision-making.

e) Optimize Budget Utilization: Ensure maximum coverage and impact under constrained financial scenarios.

f) Facilitate Policy Compliance: Aligndecisions with regulatory frameworks and organizational policies.

Step 1: Select GABM Identity Number

Each bridge management project is identified by a unique BSR[Bridge Resilience System] ID. The user selects the relevant project ID, which serves as a primary key for managing datasets associated with the project. The system allows you to select and analyze only those bridges whose data entries are within the last 10 years. This ensures that the analysis is based on up-to-date inspection records and remains relevant to current asset management priorities.

Step 2: Select Bridges for Analysis

- The user selects multiple [Maximum of 10] bridges within the chosen BRS project. If there are more bridges, the User will need to apply multiple cycles of MCDM process till all bridges are prioritized. Bridges which are defined as Critical in the RVA process are not displayed in the list of bridges under MCDM. Such bridges defined by the User as critical during RVA process will need to provided the budget for rehabilitation before application of fund optimisation process in MCDM. Such critical bridges are provided with required budget and accordingly the budget available for bridges in MCDM is reduced.
- This feature supports group analyses where funding needs are evaluated across several structures simultaneously.

Step 3: Define Criteria for Fund Optimization

The module provides a predefined list of decision criteria, which can be customized as per project requirements:

Criterion	Description
Structural Status	Evaluates the bridge's current physical condition, safety, and functionality.
Risk Assessment	Analyzes the likelihood of structural failure or operational hazards.
Financial Impact	Considers costs related to repair, maintenance, and failure consequences.
Socio-Economic Impact	Measures broader community effects, economic disruptions, and connectivity.

The user ranks these criteria by importance [1 being the highest priority]. Such ranking for the criteria determines the final outcome of MCDM.

As an example if the Structural Status is accorded Rank 1, Financial Impact Rank 2, Risk Assessment Rank 3 and Socio-economic Impact Rank 4 the outcome of MCDM will be different from the process where in the Rank are different.

Step 5: Input Organizational Budget

This User specified value is the total available budget for the selected group of bridges. This is the Budget that is evaluated based on the Initial Budget provided by the User in the Standard Parameter screen for the year in which MCDM is being applied. This is a critical input as the optimization algorithm ensures the fund distribution does not exceed this limit.

Step 6: Assign Weightage through Pairwise Comparison

After ranking the criteria, the next critical step involves assigning comparative weightages between criteria using pairwise comparisons. This enables a finer calibration of how much more important one criterion is relative to another.

User Interface Description:

The system displays pairwise comparison fields for all possible pairs of criteria. For each comparison, the user selects a weightage value between 1 to 5.

- 1: Both criteria are equally important.
- 2-5: The first criterion is increasingly more important than the second.

Pairwise Comparison Fields:

- Compare Structural Status to Risk Assessment
- Compare Structural Status to Financial Impact
- Compare Structural Status to Socio-Economic Impact
- Compare Risk Assessment to Financial Impact
- Compare Risk Assessment to Socio-Economic Impact
- Compare Financial Impact to Socio-Economic Impact

This pairwise comparison approach is aligned with the Analytic Hierarchy Process [AHP], enabling a structured and logical calculation of relative weights.

Subsequently the Screen will display the following information.

Number of Bridges on the network	
Number of Bridges which are on critical route	
Average length of Bridges on the critical route	
Expected Number of MCDM cycles	
Budget reserved for bridges on Critical route	
Budget available for bridges on non critical route	
Budget per MCDM Cycle for 10 bridges	

Step 7: Execute Analysis

Once all fields are populated [criteria rankings, weightages, and budget], the user clicks the "Select & Analyse" button.

There is also a Reset button to clear all inputs and start over if needed.

Upon clicking Select & Analyse, the system processes all the inputs through the MCDM algorithm which typically involves:

- Calculating weighted scores for each bridge based on selected criteria.
- Prioritizing bridges with critical structural or risk-related needs.
- Distributing the available budget optimally across the bridges to maximize safety, functionality, and socio-economic benefits.

ANNEXURE A -

DETAILS OF INPUT INFORMATION

Load Capacity
-- Select Load Capacity --

Upto 24R

24R

30R

40R

50R

60R

70R

HT2

Load Capacity
-- Select Load Capacity --

60R

70R

HT2

HT3

HT4

HT5

HT6

HT9 or more

Type of Road
--Select Road Type--

Waterway curvature
-- Waterway Curvature --

1-No curvature within 5 kms

2-Curvature within 3 to 5 kms

3-Curvature within 1 to 3 kms

4-Curvature within 0.5 to 1 kms

5-Curvature within 0.5 kms

Elevation of bridge
-- Select Elevation --

1 - At MSL

2 - 0 to 500 Meters Above MSL(AMSL)

3 - 500 Meters AMSL

4 - 750 Meters AMSL

5 - 1000 Meters AMSL

Shape Of Pier
-- Select Shape Of Pier --

1 - Pier With Round End

2 - Pier With Pointed End

3 - Circular Pier

4 - Square Pier

5 - Rectangular Pier

Deck Rating

1. Good Condition : 0 to 5% of the area is affected by Honeycombing, Delamination, Spalling. ≤ 1 mm cracks and 1 to 1 % of exposed reinforcement. ≤ 5%of unevenness of the concrete. No section loss

2. Satisfactory Condition : 5 to 20% of the area is affected by Honeycombing, Delamination, Spalling. Partial section loss 1 to 3mm cracks and up to 20 % of exposed reinforcement. Up to 20% of the unevenness of the concrete.

3. Poor Condition : 20% to 30% of the area is affected by Honeycombing, Delamination, Spalling, unevenness and exposed reinforcement.3 mm to 5mm cracks. ≤ 5% Section loss.

4. Critical Condition : 30 to 50% of the area affected by Honeycombing, Delamination, Spalling unevenness and exposed reinforcement. 5 to 8 mm cracks. ≤ 25% Section loss.

5. Failed Condition : Bridge closed

Super Structure

1. Good Condition : 0 to 5% of the area is affected by Honeycombing, Delamination, Spalling. ≤ 1 mm cracks and 1 to 1 % of exposed reinforcement. ≤ 5%of unevenness of the concrete. No section loss

2. Satisfactory Condition : 5 to 20% of the area is affected by Honeycombing, Delamination, Spalling. Partial section loss 1 to 3mm cracks and up to 20 % of exposed reinforcement. Up to 20% of the unevenness of the concrete.

3. Poor Condition : 20% to 30% of the area is affected by Honeycombing, Delamination, Spalling, unevenness and exposed reinforcement.3 mm to 5mm cracks. ≤ 5% Section loss.

4. Critical Condition : 30 to 50% of the area affected by Honeycombing, Delamination, Spalling unevenness and exposed reinforcement. 5 to 8 mm cracks. ≤ 25% Section loss.

5. Failed Condition : Bridge closed

Sub Structure

1. Good Condition : 0 to 5% of the area is affected by Honeycombing, Delamination, Spalling. ≤ 1 mm cracks and 1 to 1 % of exposed reinforcement. ≤ 5%of unevenness of the concrete. No section loss

2. Satisfactory Condition : 5 to 20% of the area is affected by Honeycombing, Delamination, Spalling. Partial section loss 1 to 3mm cracks and up to 20 % of exposed reinforcement. Up to 20% of the unevenness of the concrete.

3. Poor Condition : 20% to 30% of the area is affected by Honeycombing, Delamination, Spalling, unevenness and exposed reinforcement.3 mm to 5mm cracks. ≤ 5% Section loss.

4. Critical Condition : 30 to 50% of the area affected by Honeycombing, Delamination, Spalling unevenness and exposed reinforcement. 5 to 8 mm cracks. ≤ 25% Section loss.

5. Failed Condition : Bridge closed

Foundation

1. Good Condition : 0 to 5% of the area is affected by Honeycombing, Delamination, Spalling. ≤ 1 mm cracks and 1 to 1 % of exposed reinforcement. ≤ 5%of unevenness of the concrete. No section loss

2. Satisfactory Condition : 5 to 20% of the area is affected by Honeycombing, Delamination, Spalling. Partial section loss 1 to 3mm cracks and up to 20 % of exposed reinforcement. Up to 20% of the unevenness of the concrete.

3. Poor Condition : 20% to 30% of the area is affected by Honeycombing, Delamination, Spalling, unevenness and exposed reinforcement.3 mm to 5mm cracks. ≤ 5% Section loss.

4. Critical Condition : 30 to 50% of the area affected by Honeycombing, Delamination, Spalling unevenness and exposed reinforcement. 5 to 8 mm cracks. ≤ 25% Section loss.

5. Failed Condition : Bridge closed

Deck Geometry

1. Good Condition : Roadway width >7.3

2. Satisfactory Condition : 7.3≥ Roadway width ≥6.1

3. Poor Condition : 6.1> Roadway width ≥4.9

4. Critical Condition : Any width less than required for a rating code of 3 and structure is open.

5. Failed Condition : Bridge Closed

Vertical Clearance

1. Good Condition : Vertical clearance > 5.10 meters

2. Satisfactory Condition : 5.10 ≥ Vertical clearence≥4.57 meters

3. Poor Condition : Vertical clearance is less than the value in the rating code of 4 and requires corrective action.

4. Critical Condition : Vertical clearance is less than the value in the rating code of 4 and requires replacement.

5. Failed Condition : Bridge Closed

Waterway

1. Good Condition : Bridge not on water body or has Very little chances of overtopping the bridge deck and roadway approaches.

2. Satisfactory Condition : Occasional overtopping of bridge deck and roadway approaches with insignificant traffic delays.

3. Poor Condition : Frequent overtopping of bridge deck and roadway approaches with significant traffic delays.

4. Critical Condition : Occasional or frequent overtopping of the bridge deck and roadway approaches with severe traffic delays of few days.

5. Failed Condition : Bridge Closed.

ADT

1. Good Condition : <500/<500

2. Satisfactory Condition : 501 to 3000

3. Poor Condition : 3001to 6000

4. Critical Condition : 6001 to 8500

5. Failed Condition : Bridge Closed.

Social Importance

1. Good Condition : The bridge is one of the links to the island or remote area to the mainland and is the only link for connectivity.

2. Satisfactory Condition : Alternate routes and links exist but this link is important.

3. Poor Condition : Bridge eases movement from one end to other.

4. Critical Condition : The bridge structure impacts the movements in terms of time and effort needed to overcome the obstacle.

5. Failed Condition : Bridge Closed.

Economic Growth

1. Good Condition : The bridge connects two important economic areas which are inter-dependent on each other.

2. Satisfactory Condition : There is a moderate economic effect of the bridge on the areas which it connects.

3. Poor Condition : There is a negligible impact of the bridge on economic activity in the area.

4. Critical Condition : The bridge does not have any impact on the economic growth.

5. Failed Condition : Bridge Closed.

Alternate Route

4. Good Condition : 35 to 50 Kms/ Additional 90 minutes

3. Satisfactory Condition : 15 to 35 Kms/ Additional 65 minutes

2. Poor Condition : 6 to 15 Kms/ additional 35 minutes

1. Critical Condition : 1 to 6 Kms/ Additional 20 minutes

Failed Condition : Bridge Closed.

Enviorno Impact

1. Good Condition : Minor impact of the bridge on wildlife and marine/ water life exists.

2. Satisfactory Condition : Moderate to the major impact of the bridge on wildlife and marine/ water life exists.

3. Poor Condition : A major impact of the bridge has occurred and progressing due to non-corrective measures.

4. Critical Condition : A bridge is closed temporarily to implement corrective measures.

Impact

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Local damage of a concrete cover or spalling of concrete edges.

3. Poor Condition : Serious defects (crushing of concrete, severe cracking, excessive deformations or rupture of some reinforcement bars).

4. Critical Condition : Destruction of structures and dangerous defects leading to global failure of structural members and core damage is seen.

5. Failed condition : Section Failed.

Erosion

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : The softened surface is vulnerable to removal by water flow with or without suspended particles.

3. Poor Condition : Salt scaling extends several millimetres in depth. Distinctive white salt deposits are visible. Extensively removed particles of concrete, and extensive cavitation damage.

4. Critical Condition : Soil has been washed away due to fast flow and resulting in the banks of the waterway becoming unstable and useless. Cavitation damages core concrete.

5. Failed condition : Section Failed.

Abrasion

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : The fine and coarse aggregate is exposed.

3. Poor Condition : Detachment of concrete is evident.

4. Critical Condition : Extensive Detachment of concrete observed and core damage is seen.

Overload

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Flexural Cracking on the lower surface of the concrete deck slab and sagging of concrete is evident, evident of cracks at supports.

3. Poor Condition : Cracks observed, spalling of concrete, exposed reinforcement and permanent deformation was observed.

4. Critical Condition : Cracks were observed in all components of the bridge, Extensive Spalling of concrete and exposed reinforcement were observed and the core is seen.

5. Failed condition : Section Failed.

Fatigue

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : The propagation of micro-cracks was observed.

3. Poor Condition : Excessive development of diagonal cracking progressed to Spalling of the concrete, deformation, and extensive vibrations are noticed during any movement of vehicles.

4. Critical Condition : Diagonal crack has propagated across the entire section, crushing the concrete in the compressive zone above the shear crack, Core Damage is seen and the concrete section is visible to approach failure.

5. Failed condition : Section Failed.

Temperature

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Minor Cracking of both the cementitious paste and aggregates due to expansion. Colour of the concrete changes to pink in an extensive area.

3. Poor Condition : Cracks become very pronounced and increased extensively, and spalling of concrete is observed, Colour of the concrete changes to buff.

4. Critical Condition : Cracks and spalling of concrete were observed extensively on all bridge components.

5. Failed condition : Section Failed.

Shrinkage

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Cracks that run to the mid-depth of the concrete, are distributed across the surface unevenly and are usually short in length (Below 1 mm).

3. Poor Condition : Shrinkage cracks are leading to chloride attached in Reinforcement.

4. Critical Condition : Extensive corrosion of reinforcement observed.

5. Failed condition : Section Failed.

Settlement

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Significant micro-cracking on the foundation near the settlement area even with the uniform settlement, Evidence of Change in the vertical alignment of the bridge substructure.

3. Poor Condition : Cracks were observed in the superstructure, deflection in the overall frame, and settlement/tilting.

4. Critical Condition : Cracks were observed in all components of the bridge, Concrete section was severely damaged along with settlement/tilting.

5. Failed condition : Section Failed.

Chloride

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : The presence of Micro-cracks at some locations parallel to the reinforcement and these cracks changes (1-2 mm).

3. Poor Condition : Extensive Delamination and start of Spalling due to Primary Reinforcement / Extensive Delamination of Concrete in Secondary Reinforcement.

4. Critical Condition : Extensive Spalling in Primary Reinforcement / Secondary Reinforcement, Loss of Section in Rebar / Discontinuity Partial Loss of Section in Rebar, sectional integrity close to failure with core damage seen.

5. Failed condition : Section Failed.

Sulphates

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Formation of Cracks in the extensive area, increase in the volume of affected concrete. More pronounced near the ground in case of attack from groundwater.

Carbonation

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : The presence of Micro-cracks at some locations parallel to the reinforcement and these cracks changes (1-2 mm).

3. Poor Condition : Extensive Delamination and start of Spalling due to Primary Reinforcement / Extensiv Delamination of Concrete in Secondary Reinforcement.

4. Critical Condition : Extensive Spalling in Primary Reinforcement / Secondary Reinforcement, Loss of Section in Rebar / Discontinuity Partial Loss of Section in Rebar, sectional integrity close to failure with core damage seen.

5. Failed condition : Section Failed.

Alkali Aggregate

1. Good Condition : No visual distress or deterioration observed.

2. Satisfactory Condition : Map-cracking in lightly reinforced large members and end of cross-beams .

3. Poor Condition : Small portions of the concrete above the reactive silicon aggregate lift (pop-out phenomenon).

4. Critical Condition : Increasing deterioration and a further percentage of humidity will accelerate the reaction process, with the added risk of deterioration due to freeze-thaw cycles and core damage is seen.

5. Failed condition : Section Failed.

PART B:

TRANSGRESSING FROM BRIDGE MANAGEMENT TO BRIDGE RESILIENCE: CRITICAL IMPERATIVENESS, NECESSITY AND IMPACT ON BRIDGES

TRANSGRESSING FROM BRIDGE MANAGEMENT TO BRIDGE RESILIENCE: CRITICAL IMPERATIVENESS, NECESSITY AND IMPACT ON BRIDGES

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Abstract:

Bridges are critical components of transportation infrastructure because they provide continuous connectivity for people, goods, emergency services, and economic activities. However, ageing, progressive deterioration, increasing traffic demand, and exposure to flooding, earthquakes, landslides, extreme rainfall, and other hazards can progressively reduce their ability to provide safe and reliable service. Failure or prolonged closure of an important bridge can also create consequences well beyond the structure itself by affecting transportation networks, emergency response, communities, and regional economic activity.

Traditional Bridge Management Systems primarily emphasize inspection, condition assessment, maintenance, and rehabilitation. These activities remain essential, but condition alone cannot fully represent future hazard performance or the consequences of bridge disruption. This paper presents the Bridge Resilience System (BRS) as an integrated approach combining structural condition, deterioration, multi-hazard exposure, vulnerability, functional importance, socio-economic consequences, network effects, lifecycle cost, and intervention planning. Multi-Criteria Decision Making is incorporated to support transparent prioritization under limited financial resources.

The approach is demonstrated through a pilot assessment in Kolhapur District considering flooding, landslides, earthquakes, and indirect cyclone effects. The results indicate that bridge risk and intervention priority should not be determined from structural condition alone. Integrating deterioration, hazard exposure, criticality, survival-related characteristics, consequences, and

financial feasibility provides a stronger basis for proactive resilience planning and sustainable logistic infrastructure.

Note: For BRS application images, please refer the Annexure A below-

1. Introduction:

Bridges form an essential part of transportation infrastructure and connect communities, cities, industrial areas, commercial centres, and essential services. Their importance becomes particularly evident during emergencies, when reliable routes are required for evacuation, rescue operations, healthcare access, and movement of essential supplies. The failure or prolonged closure of a strategically important bridge can therefore affect transportation continuity, increase travel time, interrupt freight movement, and create difficulties for communities and emergency services.

Most bridges are designed for long service lives, but their components are continuously exposed to traffic loading, moisture, temperature variation, corrosion, fatigue, scour, environmental conditions, and maintenance-related influences. As deterioration progresses, structural capacity and performance can change. The challenge becomes more significant when an ageing bridge is exposed to an extreme event. A bridge that performs satisfactorily under normal operating conditions may have a substantially smaller safety margin during severe flooding, earthquake loading, landslides, or scour.

Traditional bridge management provides valuable information through inspection, condition assessment, maintenance, and rehabilitation. Nevertheless, condition rating alone cannot explain the complete level of risk. Two bridges with similar physical conditions may have very different consequences if one is located on a major transportation corridor while the other has practical alternative routes. Similarly, a moderately deteriorated bridge may require urgent attention when it is the only connection serving communities, emergency facilities, or important economic activity.

The changing hazard environment further strengthens the need for a resilience-oriented approach. Flooding, extreme rainfall, earthquakes, landslides, cyclonic systems, erosion, and scour may occur independently, sequentially, or in combination. Their effects can interact with pre-existing deterioration and create consequences that are not captured by a conventional inspection rating. The Kolhapur pilot considered in this study demonstrates the value of combining hazard exposure, bridge condition, functional importance, and socio-economic consequences.

The objective of this expanded study is to integrate deterioration, multi-hazard exposure, vulnerability, network criticality, socio-economic consequences, survival capability, lifecycle cost, and financial decision-making within a common bridge-resilience framework. The central proposition is that bridge management should progressively move from asking only what the present condition of a bridge is to asking how it is likely to perform, what consequences may follow disruption, and where resilience investment will provide the greatest value.

2. Limitations of Conventional Bridge Management and the Need for a Resilience-Based Approach

Conventional Bridge Management Systems (BMS) play an important role in maintaining the safety and serviceability of bridge infrastructure. Regular inspections, condition ratings, maintenance activities, and rehabilitation planning provide essential information about the present state of a bridge. However, increasing infrastructure complexity has created a need to consider factors beyond the physical condition of an individual structure.

A major limitation of a condition-based approach is that present condition does not necessarily represent future risk. A bridge may have an acceptable inspection rating while being exposed to significant flood, seismic, landslide, or scour hazards. Conversely, a bridge with severe visible distress may not represent the highest network priority when failure would have limited consequences and suitable alternatives are available.

Another limitation is the separate treatment of hazards. Heavy rainfall may produce flooding and landslides, flooding may cause scour, and a subsequent earthquake may act on components already weakened by deterioration. The resulting risk is therefore a dynamic interaction rather than a simple collection of independent hazard ratings.

Financial planning creates an additional challenge. Authorities generally operate with restricted annual budgets and cannot strengthen or rehabilitate every bridge simultaneously. A resilience-based framework must therefore connect technical risk with intervention cost, consequences of delay, and the benefits of maintaining connectivity.

- Present condition versus future performance
- Single-hazard assessment versus multi-hazard interaction
- Individual asset assessment versus network consequences
- Repair expenditure versus lifecycle value
- Reactive intervention versus proactive risk reduction

The transition from BMS to BRS should therefore be understood as a transition from managing bridge condition to managing bridge risk, continuity of service, and long-term infrastructure resilience. BMS remains an essential foundation; BRS extends that foundation by introducing a forward-looking decision layer.

3. Urbanization a global reality

Urbanization is engulfing the world, India is no exception. Statistical data proves India is one of the fastest urbanizing countries in the world. This is fueled by increasing migration to cities driven by industrialization, economic growth, and expanding employment opportunities. As urbanization grows, the rapid degradation of livability also happens unless the authorities plan to maintain it. Urban livability refers to the extent to which a city provides a safe, healthy, inclusive, and sustainable environment that enables people to live productive and fulfilling lives. It encompasses not only the quality of physical infrastructure but also access to transportation, healthcare, education, housing, employment opportunities, public spaces, environmental quality, and essential services. Urban livability has become a central objective of sustainable urban development and infrastructure planning. Rapid urban expansion often overwhelms infrastructure capacity. This leads to traffic congestion, environmental degradation, inadequate public services, and increased exposure to disaster risks. These challenges highlight the need for a planned resilient urban infrastructure capable of supporting future urban growth.

Livable cities are characterized by reliable transportation systems, efficient public services, accessible healthcare and education. The provide for environmental sustainability, social inclusiveness, economic vitality, and resilience to natural and human-induced hazards. Among these characteristics, transportation connectivity is fundamental because it supports mobility, emergency response, economic activities, and social interactions. The uninterrupted functioning of transportation infrastructure significantly influences overall urban performance and community well-being. Dynamism in severity and frequency of natural hazards such as floods, earthquakes, cyclones, and landslides frequently disrupt transportation networks and essential services. Critical infrastructure including transportation networks, bridges, roads, water supply systems, power grids, communication systems, and healthcare facilities —forms the backbone of urban development. These systems are highly interconnected, meaning the failure of one component can significantly affect the performance of others. Therefore, strengthening critical infrastructure resilience is essential for maintaining urban functionality and improving the overall livability of cities.

3.1 Bridge Infrastructure and Urban Livability

Bridges are among the most critical components of transportation infrastructure. Their strategic importance extends beyond structural functionality, as they enable access to healthcare facilities, educational institutions, workplaces, emergency services, and commercial centers. Consequently, the operational performance of bridges directly influences the efficiency and resilience of urban transportation systems. Damage or closure of bridges can result in significant traffic disruptions, increased travel distances, and reduced accessibility to essential services, thereby affecting the daily lives of urban residents. Bridges promote social inclusion by connecting communities separated by rivers, valleys, rail corridors, or other geographical barriers. Efficient and resilient bridge infrastructure contributes to economic growth by supporting freight transportation, supply chains, industrial development, and commercial activities. Bridge failures may disrupt logistics, increase transportation costs, delay business operations, and reduce regional productivity. Resilient bridge infrastructure plays an important role in sustaining urban economic development. During disasters, bridges become critical evacuation routes and emergency access corridors. Emergency response agencies rely on bridge functionality to transport rescue personnel, medical assistance, relief supplies, and essential equipment. Bridge resilience directly influences disaster preparedness, emergency response effectiveness, and post-disaster recovery. Investing in bridge resilience therefore represents an investment in improving the long-term sustainability and livability of urban environments.

4. Risks to Urban Bridge Infrastructure

4.1 Multi-Hazard risks

Bridge infrastructure is exposed to multiple hazards. Urban bridges are no exceptions. A multi-hazard perspective recognizes that different hazards may interact and collectively influence bridge performance. Understanding these interactions is essential for developing resilient transportation systems. The main natural hazards affecting bridge infrastructure include earthquakes, floods, cyclones, landslides, riverbank erosion, and extreme rainfall among others.

These hazards can cause structural damage, foundation instability, scour, deck displacement, bearing failures, and complete bridge collapse. Their frequency and intensity vary depending on geographical location and climatic conditions. Distress caused is rarely visible and hence escapes attention. Climate change has intensified the occurrence of extreme weather events, increasing the vulnerability of transportation infrastructure. Future infrastructure planning therefore must incorporate climate adaptation measures. Aging infrastructure further increases vulnerability, particularly where maintenance and inspection practices are insufficient.

Multiple hazards may occur sequentially or simultaneously, creating complex interactions that amplify infrastructure damage. Distress during one occurrence will make the bridge susceptible to failure during the next occurrence. This essentially require integrated assessment approaches rather than isolated hazard evaluations. Bridge failures resulting from multi-hazard events extend far beyond structural damage. Understanding multi-hazard risks is a critical step toward developing resilient bridge infrastructure that supports the broader objective of creating livable cities.

4.2 Cascading Effects and Infrastructure Inter-dependencies

Cascading Hazard Theory: Urban infrastructure systems are highly interconnected, meaning that the failure of one component can trigger a sequence of disruptions across multiple sectors. Such phenomena, referred to as cascading effects, occur when an initial hazard causes secondary failures that extend beyond the directly affected infrastructure. Unlike isolated failures, cascading effects amplify disaster impacts by disrupting transportation, utilities, communication, healthcare, emergency response, and economic activities. Understanding these interactions is therefore essential for developing resilient urban infrastructure systems that can withstand and recover from multi-hazard events. Urban systems consist of interconnected transportation, power, water, communication, healthcare, and emergency management networks. Transportation bridges serve as critical links within these networks.

Consequently, bridge disruptions often extend beyond transportation, affecting access to hospitals, public services, industrial zones, and residential communities. These inter-dependencies necessitate infrastructure planning approaches that consider the performance of the entire urban system rather than individual assets alone.

Bridge failures initiated by earthquakes, floods, landslides, cyclones, or other hazards can trigger extensive disruptions throughout transportation networks. Closure of critical bridges may increase travel distances, isolate communities, delay emergency response, interrupt freight movement, and reduce accessibility to essential services. These disruptions can propagate rapidly across the urban network, resulting in prolonged recovery periods and increased socio-economic losses. Therefore, bridge resilience assessment should account for both direct structural damage and indirect system-wide consequences. The consequences of bridge disruption extend to emergency medical services, disaster response operations, public transportation, utility maintenance, and supply-chain continuity. Since bridges form critical components of transportation networks, enhancing their resilience directly contributes to urban mobility, emergency preparedness, economic continuity, and social connectivity. Accordingly, cascading hazard assessment provides an important basis for identifying infrastructure vulnerabilities and prioritizing resilience investments that support long-term urban livability.

5. MCDM the game changer:

Multi-Criteria Decision Making [MCDM] enhances decision-making by utilizing multiple criterion. MCDM methodologies, such as the Simple Multi Attribute Rating Technique [SMART], and Analytic Hierarchy Process [AHP] explored to optimize resource allocation in bridge management. Fund allocation in bridge management aims to ensure efficient maintenance, upgrades, and resilience across global regions through Multi-Criteria Analysis [MCA]. Criteria prioritization includes safety, structural integrity, operational efficiency, resilience against natural disasters, and socio-economic impacts like economic benefits and community advantages. Assessing distress levels and service life balance of bridges across different regions guide's maintenance prioritization, and optimizing fund utilization. Enhancing resilience in bridges on critical routes ensures operational continuity during disruptions, minimizing economic impact and long-term repair costs. In recent years, natural hazards presents a very challenging situation for bridges, clubbed with natural hazard's frequencies and severity are becoming difficult to predict. These natural hazard's forces pose a challenge to the stability of the bridges. Symptoms often serve as early indicators of underlying structural issues. To comprehend the impact of natural hazards on the deterioration process, one must first recognize the subtle yet telling symptoms exhibited by existing bridges. All bridge structures have a very predominant deterioration process. Recent research, confirms that symptoms are indicative of deterioration process only in the early ages of the bridge life period. Based on the Design Service Life [DSL] in the early age, below 20 percentage of DSL, symptoms are sufficient indicators of deterioration. Beyond 20 percentage of DSL, symptoms alone, may not identify correctly the deterioration model. Various early age symptoms may help to identify the Principal Cause. There could be multiple causes, which manifest the entire deterioration model. EN1504 researched and published in Nineties; define three main processes that can result in deterioration in concrete. When age of the bridge structure is beyond 20 percent of DSL, identification of cause is feasible. Identification of Cause helps the bridge inspection teams from the age between 20 to 60 percent of DSL. Impact of aging in the bridge structure is pronounced when age of the bridge exceed 60 percent of DSL. Bridge inspection teams have then to rely on Short term monitoring of components of the bridge structure, which show persistent symptoms. Structural Health Monitoring [SHM] adopted for short duration (36 – 48 hours) and then repeated three to four times, at intervals of three to four months, reveal the decrement in performance. Past research in SHM have recognized that as deterioration progress, performance decreases.

The four criterion adopted with MCDM are Structural status, Risk assessment, Financial due diligence, and Socio-economic impact. The emergence of multi-criteria requires assigning importance to all four criteria based on their criticality. The assignment of values will need to be in a common scale. Financial costs would require a scale that provides information about the high cost or lower cost. Whereas the resilience of bridge would need to have scale that indicate need for enhancement. Since the users of Multi-Criteria Decision-making are varied, importance of criteria may vary. The first step would be for the user to rank the four criteria as per their importance. Incorporation of comparison between two criteria at one instance to evaluate which of the two is more important, then comparing the important criteria with the third criteria to decide which is more important and finally the comparison of the forth criteria with the selected important criteria. This simple comparison algorithm will help the user rank the criteria. Next step entails assignment of score for each criterion as per value function scale. Most of the data essential for this definition is available within BRS. Proper definition of value function scale provided within the software. The evaluation of combined score and weightage to the criteria done using the simple additive model. Simple weighted score technique deployed. Score assigned in that criterion multiplied by Weightage assigned to each criterion. The highest of the weighted score indicates the importance of the bridge for fund allocation under that criterion. Four criteria may yield different bridges. Accordingly, ranking assigned to the set of bridges for which MCDM is applied. Typical comparison of ranked bridges remedial intervention [RI] costs to the available budget of the department yields a set of bridges, for which RI provided.

The detailed process of application of MCDM is as under:

Apply Simple Multi Attribute Rating Technique [SMART]

Road authorities or Road/ Highway Concessionaire corporate identity use Bridge Management. By default, such agencies are the decision-making authorities. The objective of optimal fund allocation now changes from being mono-criterion to multi-criteria. Four alternatives / criteria now essential decide the priority of fund allocation. The criteria that now needs inclusion in decision-making protocol are:

- Distress in bridge
- Economic growth potential of the bridge
- Socio-economic importance of the bridge
- Vulnerability and risk to bridge from natural hazards needing enhanced Resilience in bridges.

This emergence of multi-criteria requires assigning importance to all four criteria based on their criticality. The assignment of values will need to be in a common scale. Financial costs would require a scale that provides information about the high cost or lower cost. Whereas the resilience of bridge would need to have scale that indicate need for enhancement. We assign value function additive model.

Since the users of Multi-Criteria Decision-making are varied, importance of criteria may vary. The first step would be for the user to rank the four criteria as per their importance. Incorporation of comparison between two criteria at one instance to evaluate which of the two is more important, then comparing the important criteria with the third criteria to decide which is more important and finally the comparison of the forth criteria with the selected important criteria. This simple comparison algorithm will help the user rank the criteria.

Compare Criteria A with Criteria B; Select more important, Say Criteria B.

Compare Criteria B with Criteria C; Select more important, Say Criteria B.

Compare Criteria B with criteria D; Select more important, Say criteria D.

Rank first position; Say Criteria 1

Now using the remaining three criteria rank Criteria 2

Similarly evaluate Criteria 3.

The last remaining criteria ranked as Criteria 4.

To each of the ranked criteria the software assigns weights.

Criteria 1 assigned 0.35,

Criteria 2 assigned 0.3,

Criteria 3 assigned 0.2, and

Criteria 4 assigned 0.15

Next step entails assignment of score for each criterion as per value function scale. Most of the data essential for this definition is available within GABM. Proper definition of value function scale provided within the software. Scale used from 1 to 5

Table 1: Assignment of score for each criterion as per value function scale

Scale value	Description
1	Best performance within the criteria
2	Very good performance
3	Good performance
4	Moderate performance
5	Worst performance within the criteria

For four criterion used within MCDM, the rating definitions are as under:

Table 2: MCDM rating

Structural status / Level of distress		Economic growth potential	
Scale value	Description	Scale value	Description
1	Structure is sound / minor distress observed. Avg. BSRN less than 2	1	Tangible IRR divided by Nontangible IRR less than 1.25
2	Structure is stable / moderate distress observed locally. Avg. BSRN greater than 2 but less than 2.75	2	Tangible IRR divided by Non-tangible IRR greater than 1.25 but less than 1.5
3	Structure shows extensive moderate distress. Avg. BSRN greater than 2.75 but less than 3.5	3	Tangible IRR divided by Non-tangible IRR greater than 1.5 but less than 1.75
4	Structure shows extensive severe distress. Avg. BSRN greater than 3.5 but less than 4.0	4	Tangible IRR divided by Non-tangible IRR greater than 1.75 but less than 2.0
		5	Tangible IRR divided by Non-tangible IRR greater than 2.0

5	Structure shows extensive very severe distress. Avg. BSRN greater than 4.0

SOCIO- ECONOMIC IMPACT

1	Non-Tangible IRR less than 15
2	Non-Tangible IRR greater than 15 but less than 20
3	Non-Tangible IRR greater than 20 but less than 23
4	Non-Tangible IRR greater than 23 but less than 25
5	Non-Tangible IRR greater than 25

RISK ASSESSMENT

1	Combined Vulnerability index and Combined Risk index both less than 0.15
2	Combined Vulnerability index and Combined Risk index both greater than 0.15 but less than 0.2
3	Combined Vulnerability index and Combined Risk index both greater than 0.2 but less than 0.23
4	Combined Vulnerability index and Combined Risk index both greater than 0.23 but less than 0.27
5	Combined Vulnerability index and Combined

Risk index both greater
than 0.27

The evaluation of combined score and weightage to the criteria done using the simple additive model. Simple weighted score technique deployed. Score assigned in that criterion multiplied by Weightage assigned to each criterion. The highest of the weighted score indicates the importance of the bridge for fund allocation under that criterion. Four criteria may yield different bridges. Accordingly, ranking assigned to the set of bridges for which MCDM is applied. Typical comparison of ranked bridges remedial intervention [RI] costs to the available budget of the department yields a set of bridges, for which RI provided.

The overall policy of the user organization dictates the importance of the criteria. The organization allocates annual budget every year in advance. This allocation is restrictive. It does not necessarily cover every bridge need for allocation. The application of MCDM arises in this scenario. Three different outcomes may be feasible. The option to provide fund, not to provide fund and retain option to provide fund on priority next year. The third option does not require that bridge to application of MCDM in the next financial cycle. This creates three level of multi attribute in decision-making. The focus of MCDM is Optimize Fund allocation. This is the first level of choice making. There are four criteria to decide this allocation. This is second level of choice making. Overriding necessity of few bridges for fund allocation necessitates third level of choice. The tangle arises post one round of MCDM. Analytical Hierarchy process application solves the tangle.

Bridges to which RI provision is not feasible due to paucity of budget form a set to which we apply further analysis. Application of normalized score technique yields a fresh ranking for bridges within this set. The final ranking for all bridges then compiled. A reduction of estimated budget introduced to ensure all bridges get funds in their ranked priority manner so that every bridge attended.

6. Interaction Between Bridge Deterioration and Natural Hazards

Bridge deterioration is a continuous process beginning from the time a structure enters service. Traffic loading, moisture, temperature variation, corrosion, fatigue, poor drainage, environmental exposure, and inadequate maintenance gradually affect different bridge components. A bridge can remain operational while its residual capacity and safety margin are progressively reduced.

The relationship between deterioration and hazards is not simply additive. A deteriorated bridge may respond very differently to the same hazard as a bridge in good condition. A weakened foundation may perform satisfactorily during normal river flow but become critical when flood velocity and scour increase. Similarly, cracking or corrosion may not immediately cause failure but may reduce the reserve capacity available during earthquake loading or exceptional traffic demand.

Repeated events create an additional dimension. Damage from an earlier event may remain partially unrepaired or undetected, leaving the structure in a weaker state before the next event. Thus, bridge condition immediately before a hazard becomes an important determinant of performance. This supports continuous monitoring and periodic reassessment rather than reliance on a single inspection record.

6.1 Component-Level Assessment

- Superstructure: corrosion, cracking, deformation, fatigue and loss of section.
- Substructure: cracking, settlement, instability and deterioration of piers or abutments.
- Foundation: scour, erosion, settlement and loss of bearing or stability.

- Bearings and joints: deterioration, movement restriction, unseating susceptibility and loss of functionality.
- Approaches and surrounding terrain: slope instability, erosion, drainage failure and access disruption.

Component-level information is valuable because different hazards act through different mechanisms. The purpose is not to assign one generic vulnerability to the bridge, but to identify which component and deterioration mechanism are most likely to govern performance under the relevant hazard.

7. Multi-Hazard Exposure and Changing Risk Conditions

Bridge infrastructure is rarely exposed to a single hazard throughout its service life. Depending on location, a bridge may experience flooding, extreme rainfall, landslides, earthquakes, cyclonic rainfall, erosion, scour, and other environmental stresses. Their intensity and frequency vary spatially and temporally, making location-specific assessment important.

Kolhapur District provides a suitable example. The district lies within multiple river basins and experiences intense seasonal rainfall. Rapid rises in river levels can produce hydraulic forces, prolonged submergence, debris impact, and foundation scour. Western hilly areas are also susceptible to landslides, while the district lies in Seismic Zone III. Historical flood events cited in the study, including 1975, 1978, 1993, 2005, 2019, and 2021, demonstrate recurring flood exposure.

Flooding is identified as the dominant and recurring hazard in the pilot, while landslides form an important secondary hazard and seismic events, although less frequent, may have severe consequences for vulnerable bridges. The purpose of multi-hazard assessment is not to predict the exact date of each event, but to identify combinations of exposure and bridge vulnerability that require greater resilience attention.

8. Risk and Vulnerability Analysis [RVA]- The essential feature for Multi-Hazard analysis:

8.1 RVA definition and Objectives in BRS

BRS is proposed as an integrated digital decision-support platform for managing bridge infrastructure under multi-hazard conditions. Unlike conventional bridge management systems that primarily focus on inspections and maintenance, the BRS combines bridge inventory, condition assessment, hazard analysis, vulnerability evaluation, resilience assessment, rehabilitation planning, financial analysis, and decision support within a unified framework. This integrated approach enables infrastructure owners to transition from reactive maintenance practices to proactive resilience-oriented management strategies. Through centralized data management and analytical tools, the BRS supports evidence-based prioritization of interventions, optimized allocation of financial resources, and long-term enhancement of bridge resilience. In the context of bridges, Risk is defined as the probability of a hazardous event occurring combined with the consequences that follow, such as structural failure, service disruption, or socio-economic losses. Vulnerability refers to the inherent weaknesses within the bridge system that make it more susceptible to damage when exposed to hazards. These weaknesses may arise from material degradation, inadequate design standards, lack of maintenance, or ageing infrastructure. Hazard itself represents the potential occurrence of a damaging event, either climatic [such as heavy rainfall, floods, or extreme heat] or geophysical [such as earthquakes and landslides]. Exposure denotes the degree to which a bridge is located in hazard-prone zones. Another important term is Balance Service Life, which refers to the remaining operational years of a bridge before it reaches a critical point where its safety and functionality could be compromised. Moreover, the impact of hazards on bridges may manifest in multiple ways: direct physical damage to the structure, deterioration of materials due to climatic stress, or indirect effects such as traffic disruption and economic losses in the connected regions. The objectives of RVA must extend beyond broad goals like sustainability and instead emphasize operational resilience. The primary objective is to ensure that bridges remain functional during and after hazard events, thereby safeguarding connectivity for life-saving rescue and relief operations. The specific objectives include:

- Identifying vulnerabilities in bridge structures under climate and natural hazard conditions.
- Quantifying risks to prioritise interventions.
- Guiding adaptation measures to extend the balance service life of bridges.
- Supporting policy decisions for investment in resilient infrastructure.

The outcomes of RVA are measurable and include increased structural reliability, reduced disruption during disasters, and enhanced preparedness. However, several challenges exist, such as incomplete hazard data, difficulty in predicting future climate dynamics, financial constraints, and variations in local capacity for implementation. Addressing these challenges is critical for translating RVA into practical resilience strategies.

Bridges are long-life structures designed to perform safely and reliably over decades, often exceeding 50–100 years of service. Their ability to withstand extreme events is largely dictated by the bridge design principles, particularly the concept of design loads. However, the challenges posed by climate variability and natural hazards highlight the limitations of traditional design approaches, which have been strongly dependent on historical climate and hazard records.

Risk is not determined by a single factor but rather emerges from the complex interplay of hazard, exposure, and vulnerability. A high-intensity hazard, such as a flood or earthquake, does not automatically translate into high risk if the bridge lies outside the hazard zone or possesses strong structural resilience. Conversely, even a moderate hazard can result in catastrophic consequences when a bridge is both highly exposed and structurally deficient. For instance, a medium-intensity flood may devastate an ageing bridge with eroded foundations located in a river basin, while a newly constructed, elevated bridge in the same area may withstand the same flood with minimal damage.

Bridge design principles rooted in historical hazard data provide a strong baseline but are increasingly inadequate under changing climatic conditions. Since design loads lock in a bridge's capacity, resilience can only be improved through modification, retrofitting, or forward-looking design approaches. A shift towards climate-adaptive and future-oriented design is therefore essential for safeguarding bridge infrastructure.

Bridge deterioration is a progressive process that directly affects the structural integrity and load-carrying capacity of a bridge. From the moment a bridge is constructed, it begins to interact with its surrounding environment, and this interaction initiates mechanisms of deterioration. The primary causes of deterioration in concrete bridges can be broadly classified into climate-dependent factors, structural factors, and human-induced factors. Among these, climate-dependent causes are the most dominant and unavoidable. In concrete bridges, deterioration often arises from environmental and climatic influences such as temperature variations, moisture ingress, freeze-thaw cycles, chloride penetration from de-icing salts or marine exposure, carbonation, sulphate attack, and corrosion of reinforcing steel. Since these factors are directly linked to the surrounding climate and natural conditions, they cannot be fully eliminated and instead must be managed through design, maintenance, and timely interventions.

The critical implication of these processes is that deterioration begins from day one of service and continues as the bridge ages, making older bridges significantly more prone to distress and failure. As deterioration progresses, the bridge's effective load-carrying capacity gradually reduces. This reduction not only compromises the safety and durability of the structure but also leads to decreased performance, affecting serviceability, reliability, and resilience against hazards. Over time, if left unaddressed, deterioration can escalate to severe structural failures, causing disruptions to connectivity and posing risks to public safety.

8.2 Vulnerability of ageing deteriorated bridges

Ageing bridges present a unique challenge in risk and vulnerability evaluation because their performance decreases steadily over time while hazard intensity and frequency are increasing due to climate change. Unlike new constructed bridges, which are designed to meet specific load and hazard criteria, older bridges experience material degradation and structural weakening that significantly reduce their load-carrying capacity. This reduction in capacity makes them more vulnerable when exposed to natural hazards such as floods, earthquakes, or cyclones. Deterioration in bridges begins from the very first day after construction, while some of these causes can be attributed to human abuse [overloading, poor maintenance, use of inferior materials], the majority are climate-dependent, such as chloride ingress in coastal regions, freeze–thaw damage in colder zones, or scouring during floods. As deterioration advances, the bridge's ability to perform as originally designed steadily declines.

8.3 Key deterioration mechanisms include:

a) Corrosion of reinforcement caused by chloride attack or carbonation, leading to cracking and spalling of concrete.

b) Fatigue of steel components due to repetitive loading from traffic.

c) Foundation weakening from scouring, which reduces stability.

d) Concrete degradation from chemical reactions [sulphate attack, alkali–silica reaction] and environmental cycles.

The consequence is a progressive reduction in residual capacity. The original design capacity, which once guaranteed safety, no longer reflects the bridge's real-time strength. This means that a bridge which may have been safe decades ago, could now be highly vulnerable, even under moderate hazards. For example, a medium-intensity flood might devastate an old bridge with eroded foundations, while a newer, elevated bridge may resist the same event.

To address this, it becomes essential to:

a) Conduct detailed inspections and material testing to assess the present condition.

b) Quantify residual load-carrying capacity through analytical modeling and load testing.

c) Relate this reduced capacity to the expected hazard environment to predict vulnerability more accurately.

If such evaluations are not carried out, ageing bridges can quickly transition from being functional infrastructure to high-risk liabilities. They may fail during disaster events, endangering lives, disrupting connectivity, and weakening community resilience. Thus, vulnerability of ageing bridges is not a static measure but a dynamic outcome of how deterioration processes interact with evolving hazard conditions over time. Various factors needs evaluation in the process of completion of RVA. Few key factors are outlined here.

- The Structural Vulnerability factor [SVF] depends on the age of the bridge [A], material condition [MC] and design of the bridge [DP] apart from the Bridge Structural Rating Number. The mean of the BSRN is modified to account for the age of the bridge and the material condition for a specific design philosophy.

$$\mathbf{SVF} = f\,[A, MC, DP] \quad \ldots \quad \mathbf{1}$$

- The functional importance factor [SIF] depends on the values assigned during inspection to the Functional parameters, namely the Bridge geometry [BG], Bridge vertical clearance [VC], Waterway adequacy [WA], and average daily traffic [DT]on the bridge.

$$\mathbf{SIF} = f\,[BG, VC, WA, DT] \quad \ldots \quad \mathbf{2}$$

- Socio-economic importance [SEIF] of the bridge contributes to the definition of vulnerability and hence to the evaluation of the risk index.

Parameters like social importance [SI], Economic growth potential [EGP] due to the bridge, Environmental impact [EI] contributed by the bridge.

$$\textbf{SEIF} = f\,[SI, EGP, EI] \;\ldots\; \textbf{3}$$

- Bridge Importance Factors [BIF] decided by the importance of the bridge in evacuation and rescue [C_r]operations. This factor is critically determined by the traffic on the bridge [DT] and the alternate route parameter [AR], which determines how much more time the vehicle needs to travel in the absence of the bridge.

$$\textbf{BIF} = f\,[C_r, DT, AR]\ldots \quad \textbf{4}$$

All the above factors are modified as per the regional hazard frequency [F] and severity dynamics [S]. $\textbf{RF} \propto \textbf{F, S} \ldots\ldots \quad \textbf{5}$

- Finally, all these five factors are used to determine the fraction assignment [RHFA]

$$\textbf{RHFA} = f\,(SVF, SIF, SEIF, BIF] + f\,[RF)\ldots \quad \textbf{6}$$

from which the weighted RVA score for the bridge is evaluated.

$$\textbf{RS} = RFr + RHFAr\ldots\ldots\ldots \quad \textbf{7}$$

The summation of all four scores determines the Risk score, which is then used to assign the risk index based on the zone in which the bridge is located.

$$\textbf{RI} = RS \;/\; max[RHFA] \ldots\ldots \quad \textbf{8}$$

9. Ageing, Deteriorated Bridge failure analysis – A breakthrough

Globally all existing bridges show propagating distress. Existing bridges are in varying stage of deterioration process. This degree of distress is dependent upon the age of bridge, geospatial location, and exposure to environment. Each natural hazard has a typical force configuration that acts on the bridge structure. Increased severity of the hazard magnifies this force configuration on the bridge. The impact of such forces on the bridge structure is critically dependent upon the stage of the deterioration model of the bridge structure. When one has to evaluate the consequence of natural hazards on existing bridges, it is critical to understand and have clarity on how the forces of natural hazards will act on pre-existing deterioration model. This makes it essential to model varying deterioration stages and impose the force of natural hazard on the bridge structure. Results of such a study, enabled research define the consequences of the hazard on the bridge structure. The statistically proven four hazards analyzed majorly cause bridge collapse globally are Earthquake, Cyclone, Floods, and Landslides. Within these four hazards, the principal type of failure are -

a. Substructure failure due to shear force.
b. Superstructure overturning or toppling.
c. Superstructure unseating and then toppling

All the above failure mechanisms can cause a cascading failure to set in. A local failure in a single element has a potential to result in adjacent areas to fail. Such a cascading impact result in total collapse of a bridge. BRS evaluates the magnitude of force (due to natural hazards) essential to result in element failure under known level of pre-existing deterioration.

9.1 Seismic Resilience and Earthquake Impact

Bridges located in higher seismic zones require advanced engineering solutions to mitigate earthquake-induced forces. Shear failure of piers and superstructure displacement are common risks in earthquake-prone areas. Adequate care during design is normal, reinforcement detailing should account for seismic forces. Shear reinforcement spacing, and type of bearing enhances the bridge’s ability to absorb seismic shocks, reducing the likelihood of structural collapse. Additional considerations are required to provide for the dynamism of frequency and severity of earthquake. Analysis indicate:

- The requirement of robustness in pier and superstructure to increase the probability for survival.
- Designed pier and superstructure render the component safe, but absence of robustness leads to reduced probability of survival.
- Bridges with high level of deterioration show more susceptibility to collapse.
- As the rating for Earthquake increases, collapse susceptibility is observed even in bridge with lower deteriorated.

9.2 Flooding and Hydraulic Forces

Flooding poses a major threat to bridge stability, often leading to scour around piers and unseating of the superstructure. The depth of piers, spacing of reinforcement, and type of foundation are critical in resisting hydraulic forces. Dynamism of frequency and severity of rainfall, cyclones drought lead to increased frequency of flooding. The velocity of flowing water shows sharp increase. So also the height of flood water has increased. Such increased velocity and height causes the forces to also increase. Toppling of superstructure, shear failure of substructure has now increased. Resilience demand bridges being designed will have to be high level bridges with robust structures that can withstand dynamism of natural hazards. Analysis show:

A) The robustness in pier and superstructure results in increasing survival probability.

B) Designed pier and superstructure render the component safe, but absence of robustness leads to reduced probability of survival.

C) Bridges with low pier height are most susceptibility to collapse and failure by toppling of superstructure.

D) High level of deterioration in bridge structure show more susceptibility to collapse.

E) As the rating for Flooding increases, collapse susceptibility is observed even in bridge with lower deteriorated. It is seen that susceptibility varies with height of pier and in zones with high ratings of Flood hazard.

9.3 Landslide Susceptibility and Soil Stability

Bridges in hilly or unstable terrain are vulnerable to landslides, which can exert significant lateral forces on piers and abutments. The resilience of a bridge under such conditions depends on soil stabilization techniques, deep foundations, and retaining structures. Regular geotechnical assessments and slope stabilization measures can help reduce the impact of landslides on bridge performance. Analysis indicate:

A) The robustness in pier and superstructure results in increasing survival probability.

B) Designed pier and superstructure render the component safe, but absence of robustness leads to reduced probability of survival.

C) Bridges with low pier height are most susceptibility to collapse and failure by toppling of superstructure.

D) High level of deterioration in bridge structure show more susceptibility to collapse.

E) As the rating for landslides increases, collapse susceptibility is observed even in bridge with lower deteriorated. It is seen that susceptibility varies with height of pier and in zones with high ratings of landslide hazard

9.4 Cyclone induced structural stress

High wind speeds and heavy rainfall associated with cyclones can compromise bridge stability. The unseating of superstructures and shear failure due to wind forces are common concerns. The use of robust pier designs, additional anchorage systems, and wind-resistant bearings can enhance a bridge's ability to withstand cyclonic events. Analysis indicate the behavior to be identical to that of Flood impact bridges, probably as Cyclone results in flash flooding due to intense rainfall. The finding are similar to flooding.

10. Pilot Project findings

The Kolhapur pilot provides practical evidence supporting the integrated resilience approach. The district experiences significant monsoon rainfall and is exposed to river flooding, landslides, moderate seismic risk, and indirect cyclone-related effects. Several historical flood events demonstrate recurring exposure and the potential for disruption to bridge infrastructure.

The assessment identifies flooding as the dominant and recurring hazard, with landslides as an important secondary hazard. Several bridges were classified as high risk because hazard exposure, advanced deterioration, and functional importance occurred together. This demonstrates that high risk is not necessarily generated by one factor.

The reported bridge-level results show variation among structures. KUR Bridge, Tarmaparni Bridge, Kodoli Bridge, Majgaon Bridge, and Ichalkaranji Old Bridge are recorded with severe status and different combinations of flooding and earthquake dominance. Their reported BSL and ABSL values also differ, indicating different survival-related characteristics.

The pilot therefore supports differentiated intervention strategies. Bridges with severe condition, high hazard exposure, and high functional importance require greater attention, while medium- and lower-risk bridges can be managed through planned maintenance and monitoring. The study further reports positive benefit–cost ratios for the resilience investments considered, supporting the economic justification of resilience enhancement.

A pilot project was initiated in Kolhapur District, located at the eastern foothills of the Western Ghats within multiple river basins, is exposed to multiple natural hazards due to its tropical monsoon climate, intense seasonal rainfall, and complex geo-morphology. High-intensity monsoon precipitation often causes rapid rises in river levels, subjecting bridges to severe hydraulic forces, prolonged submergence, debris impact, and foundation scour. These conditions accelerate structural deterioration and reduce serviceability.

The district is also indirectly affected by cyclonic systems from the Arabian Sea which intensify rainfall and trigger flooding and landslides, particularly in the western hilly talukas. Additionally, Kolhapur lies in Seismic Zone III, indicating moderate earthquake risk, with many older bridges designed without modern seismic provisions. Historical flood events, notably in 1975, 1978, 1993, 2005, 2019, and 2021, highlight the vulnerability of bridge infrastructure and underscore the need for proactive, risk-based, and resilience-oriented bridge management. By integrating historical hazard data, bridge inspection records, and semi-quantitative risk analysis techniques, the pilot study provides a structured framework for evaluating bridge safety, performance, and resilience.

The primary purpose of this study is to assess the risk and vulnerability of bridges under multiple natural hazards, including floods, indirect cyclone impacts, landslides, and earthquakes. The scope covers bridges of varying age, design, material, and functional importance across state highways and major district roads, using historical data.

Key objectives include:

I. Identification of dominant hazards,
II. Assessment of structural Functional, and socio-economic vulnerability,
III. Evaluation of risk index through integration of hazard likelihood and consequences.
IV. Prioritization of bridges for mitigation and resilience enhancement.
V. RVA also provide technical inputs to support policy decisions and disaster preparedness planning.

The adopted methodology demonstrates how engineering condition data, when combined with hazard characteristics and consequence analysis, can provide a more realistic representation of infrastructure risk than conventional assessment approaches.

The multi-hazard assessment identifies flooding as the most critical and recurring threat to bridge infrastructure in Kolhapur District, primarily due to riverine flooding, high monsoon rainfall, and scour-related damage mechanisms. Landslides emerge as a significant secondary hazard, particularly in the western hilly regions where geomorphological conditions and intense rainfall increase slope instability. In addition, the district has moderate seismic risk, which, although less frequent, carries potentially severe consequences for structurally vulnerable bridges. Several bridges were classified as high risk owing to the combined effects of elevated hazard exposure, advanced structural deterioration, and high functional importance within the regional transportation network. The identification of medium- and low-risk bridges further enables a rational, phased approach to intervention, allowing authorities to allocate resources strategically while maintaining acceptable service levels across the network. The study also highlights that bridge vulnerability increases significantly when financial availability is constrained, underscoring the strong linkage between funding adequacy and infrastructure resilience.

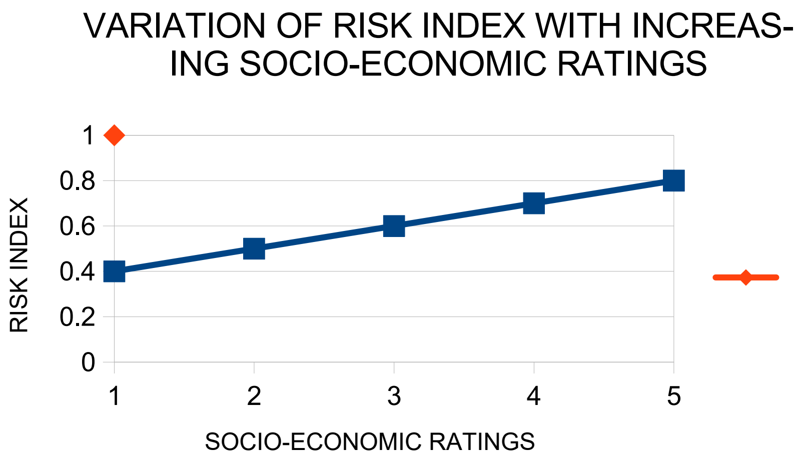
One of the most significant outcomes of this pilot project is the explicit demonstration of the limitations of conventional condition-based inspection practices when applied in isolation. While routine inspections are essential for identifying visible deterioration and structural deficiencies, they do not adequately capture the influence of natural hazard frequency, intensity, spatial variability, and cascading consequences. By contrast, the multi hazard risk-based framework adopted in this study integrates inspection data with hazard history and consequence assessment, enabling a transition from reactive maintenance toward proactive and prioritized risk-based management. This shift is particularly crucial for climate adaptation planning in districts such as Kolhapur, where bridges are repeatedly exposed to natural hazards that are expected to intensify under changing climatic conditions. The findings strongly support the adoption of risk-informed and resilience-oriented bridge management practices. The benefit–cost analysis conducted for all bridges included in the study indicates positive benefit–cost ratios, confirming that investments in resilience enhancement, retrofitting, and protective measures are economically justified.

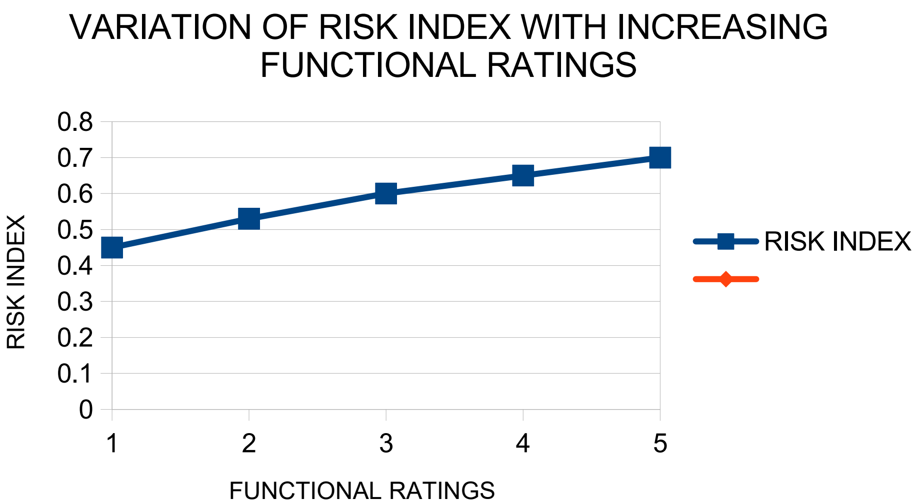
Spatial variability in risk and vulnerability across the district highlights the importance of using location-specific and context-sensitive data. The reliance on district-level datasets ensures that regional hazard characteristics, local construction practices, and network dependencies are accurately represented. The incorporation of AI-based analytical tools further strengthens the framework by accounting for the dynamism of hazard frequency and severity, allowing the assessment to reflect evolving risk conditions rather than static historical averages. Additionally, the integration of financial due diligence within the multi-criteria decision-making (MCDM) framework proves critical for realistic budgetary planning, as financial constraints directly exacerbate vulnerability and increase the overall risk index. Financial crunch will increase the risk index as the vulnerability increases.

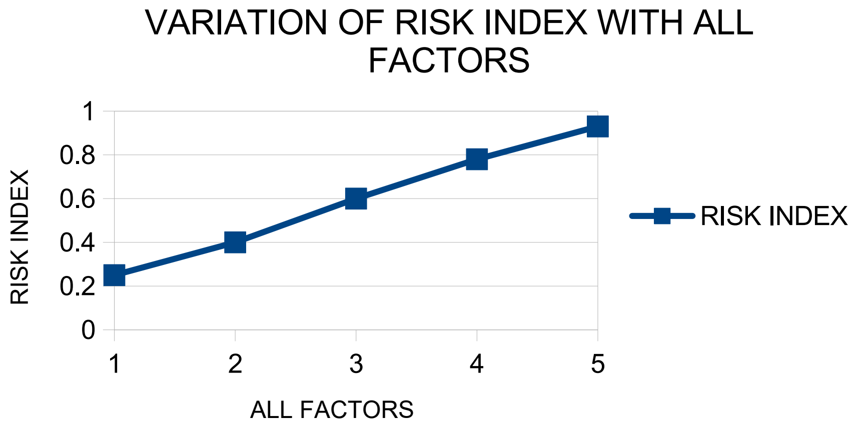
At the policy and governance level, this study emphasizes the necessity of integrating risk and vulnerability assessments into existing bridge management systems and broader climate adaptation strategies. The outcomes demonstrate how risk-based prioritization frameworks can support evidence-based decision-making, improve transparency in resource allocation, and enhance coordination between engineering, disaster management, and planning authorities. A key outcome of the study is the demonstrated importance of integrating hazard history with routine bridge inspections. Inspection data alone are insufficient to capture true risk levels without considering hazard frequency, intensity, and potential consequences. The findings support the transition toward risk-informed and resilience-oriented bridge management practices. Past natural hazards occurrence in the district have shown that failure or disruption of few critical bridges can severely affect mobility, emergency response, and regional economic stability. In this context, conventional condition-based inspection practices alone are inadequate to capture the true level of vulnerability and resultant risk. A comprehensive Risk and Vulnerability Analysis [RVA] is therefore necessary to integrate hazard exposure, bridge condition, functional importance, and potential consequences. This paper presents results of RVA conducted to support informed decision-making, prioritization of interventions, and enhancement of long-term resilience of bridge infrastructure in Kolhapur District. Typical results for few bridges are outline in Table 1. below and the variation of Risk Index with respect to various factors are presented graphically under Fig1 to Fig 4 below.

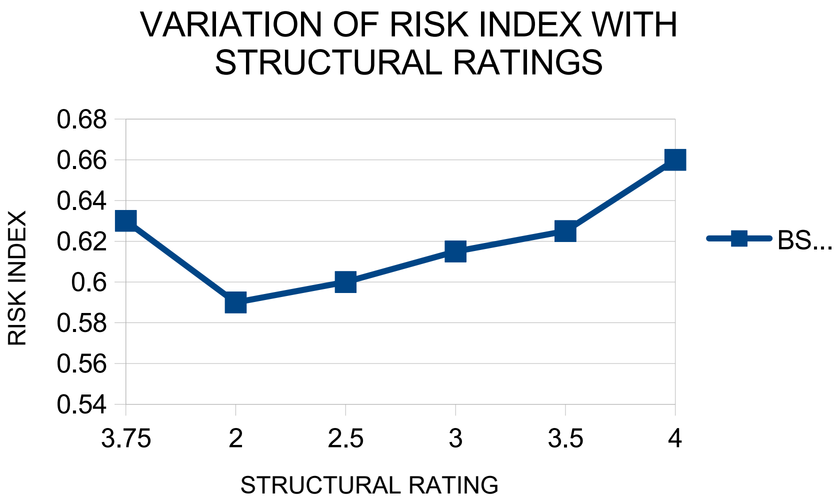
Table 3: Distribution of Hazard Dominance

BRIDGE ID	BRIDGE NAME	STATUS / CAUSE	Hazard Dominance	BSL	ABSL
MHSH0189B002	KUR BRIDGE	Severe / Mechanical	Flooding, Earthquake	5.31	1.06
MHSH0189B003	TARMAPARNI BRIDGE	Severe / Mechanical & Chemical	Flooding, Earthquake	5.36	1.29
MHSH0192B008	KODOLI BRIDGE	Severe / Mechanical & Chemical	Flooding	6.32	1.83
MHDR0018B009	MAJGAON BRIDGE	Severe / Mechanical & Chemical	Flooding, Earthquake	6.31	2.9
MHSH0192B012	ICHALKARANJI OLD BRIDGE	Severe / Mechanical & Chemical	Flooding	5.36	1.23









10.1 Risk Analysis and Evaluation

Likelihood and Consequence

Risk analysis is carried out by combining hazard likelihood with bridge vulnerability and potential consequences. Hazard probability is estimated using historical occurrence data and regional hazard characteristics. Structural vulnerability is derived from inspection and analysis results, while functional importance reflects the role of the bridge within the transportation network. These factors are integrated to assign overall risk levels to individual bridges.

Results of Risk and Vulnerability Analysis done for all bridges, the results are tabulated :

TABLE 4

BRIDGE ID	**RISK INDEX [RI]**				**RI for MCDM**
	FLOODING	CYCLONE	LANDSLIDE	EARTHQUAKE	
MHSH0189B002	0.59	0.58	0.67	0.67	0.63
MHSH0189B003	0.62	0.6	0.69	0.69	0.65
MHSH00130B004	0.61	0.59	0.68	0.68	0.64
MHSH0201B005	0.58	0.57	0.66	0.66	0.62
MHSH0397B006	0.6	0.57	0.65	0.65	0.62
MHSH0150B007	0.6	0.57	0.65	0.65	0.62
MHSH0192B008	0.61	0.59	0.68	0.68	0.64
MHDR0018B009	0.59	0.58	0.67	0.67	0.63
MHDR0039B010	0.57	0.55	0.64	0.64	0.6
MHSH0192B011	0.6	0.58	0.67	0.67	0.63
MHSH0192B012	0.64	0.62	0.71	0.71	0.67
MHSH0195B013	0.6	0.57	0.65	0.65	0.62
MHDR0053B014	0.62	0.6	0.69	0.69	0.65
MHDR0037B015	0.6	0.58	0.67	0.67	0.63
MHSH0166B016	0.66	0.62	0.7	0.7	0.67

Risk and Vulnerability analysis for all bridges has been conducted. One important factor needs to be borne in mind, when the bridge is designated for Risk and Vulnerability Analysis in GARM than that Bridge is not available in the MCDM module. This is due to the fact that bridge which is critical needs to attended first before assignment of ranking for non critical bridges.

Risk Prioritization: Based on the combined assessment, bridges are categorized into high, medium, and low risk groups. High-risk bridges are those with high hazard exposure, poor structural condition, and high functional importance.

Medium-risk bridges require monitoring and planned intervention, while low-risk bridges are suitable for routine maintenance. This prioritization supports efficient allocation of resources and targeted mitigation planning.

10.2 Consequence Assessment

Direct Impacts: Direct consequences include physical damage to bridge components, repair and rehabilitation costs, and potential replacement expenses in severe cases. These impacts represent immediate financial and technical challenges following hazard events.

Indirect Impacts: Indirect impacts include traffic delays, loss of connectivity, disruption to emergency services, and broader economic and social losses. In flood or landslide scenarios, prolonged bridge closures can significantly affect regional mobility and access to essential services.

Criticality Assessment: Criticality assessment evaluates the strategic importance of each bridge within the transport network. Bridges serving major routes, urban centers, or emergency corridors are assigned higher criticality, increasing their overall risk significance.

10.3 Mitigation and Action Plan

Structural Measures: Structural mitigation measures include retrofitting and strengthening of vulnerable components, installation of scour protection works, and replacement or rehabilitation of deteriorated bearings and joints. These measures aim to enhance structural capacity and durability under extreme loading conditions.

Operational Measures : Operational strategies focus on improving preparedness and response, including emergency action planning, traffic diversion routes, and temporary load or access restrictions during extreme events. These measures reduce risk to users and maintain network functionality.

Monitoring and Review : A systematic monitoring and review framework is proposed, incorporating periodic inspections, condition reassessment, and sensor-based monitoring for critical bridges. Integration with early-warning systems for floods and extreme weather events is recommended to support timely decision-making and reduce damage.

10.4 Risk Results and Interpretation

The pilot risk table reports bridge-level risk indices across flooding, cyclone, landslide, and earthquake conditions. The values demonstrate that risk varies between bridges and hazard categories. The results also show why the bridge selected for Risk and Vulnerability Analysis should be treated according to its criticality before applying ordinary fund-ranking procedures.

A key finding of the pilot is that routine inspection data alone do not capture hazard frequency, intensity, spatial variability, or cascading consequences. Integrating inspection records with hazard history and consequence assessment enables a transition from reactive maintenance toward proactive and prioritized risk-based management.

11. Comparison between Bridge Management and Bridge Resilience system

Table 5: Bridge Management system vs Bridge Resilience System

COMPARISON OF BRIDGE MANAGEMENT SYSTEM [BMS] AND BRIDGE RESILIENCE SYSTEM [BRS]		
DETAILS	**BMS**	**BRS**
Definition	Frameworks designed to facilitate the management of bridges, optimising budgets while ensuring adequate structural performance.	Framework designed to facilitate management of bridges ensuring a proactive approach to optimizing budgets to facilitate enhancement of resilience and rehabilitation to ensure adequate structural performance.
Key focus	Symptoms based deterioration modeling to	Selection of parameter [symptoms / cause of distress / performance of

	determine BSL, ABSL	bridge] based on age to define deterioration modeling to determine BSL, ABSL, MSL
Yields fund optimisation based on	BSL, ABSL and symptoms driven deterioration modelling with focus only on severity of distress. Mono-Criterion approach for fund allocation and optimisation.	Adopts Multi-Criteria Decision-Making process for fund optimisation and management. Allows user to determine weight age that defines the relationship between four criterion. Focus is on Multi-Criteria
Rehabilitation interval decision	Reactive approach to decides the Rehabilitation interventions required.	System has a Pro-active approach to define the intervention interval. Results in avoidance of increment in distress.
Results provided within the framework	Determines BSL, ABSL	Determines BSL, ABSL, MSL, IRR, RI, VI and probability of bridge survival for natural hazards occurrences
Additional processes performed	No additional process	Performs Whole life cycle cost analysis, Risk and Vulnerability Analysis, Multi-Criteria Decision-Making process, Bridge Survival probability evaluation

Table 6: High-points of Bridge Resilience System

SUMMARY OF BRIDGE RESILIENCE SYSTEM	
FUNCTIONALITY	**THEORIES, TECHNIQUES & TECHNOLOGIES**
Data collection, acquisition and processing.	Finite Element Analysis[FEM], Machine Learning based Artificial Learning. Convolution Neural Network. Global Positioning System, HTTP protocol, MySQL, Dot net techniques, Large scale Big-Data processing tools, Cloud storage, Common Data Environment for information management, 3D photogrammetry tools,
Bridge Deterioration modeling	Stochastic and Deterministic methods using Markov Chain model, Probability methods, Weibull distribution models, Bayesian Belief Networks, Reliability based theories are all integrated within the Machine learning protocol to select the input data based on age of the bridge. Corrosion theory, Environmental impact studies, Age related Fatigue analysis are combined within the Machine learning protocol. Structural mechanics and basic physical theories
Balance Service life, Absolute Balance Service life and Median Service life	Deterioration theories like Stochastic and Deterministic methods using Markov Chain model, Probability methods, Time based reliability theory, Probabilistic design theory. Markov Chain approach modelling of bridge condition to

	predict likelihood of bridge components moving from one state of deterioration to the next. Grey relational analysis to overcome insufficient data situation and finally Bayesian theory. Corrosion theory, Environmental impact studies, Age related Fatigue analysis are combined within the Machine learning protocol. Structural mechanics and basic physical theories integrated with basic structural mechanics and load transfer theories.
Internal Rate of Return evaluation	Basic Life cycle cost analysis [LCCA] principles applied to whole life of the Bridge. Evaluation of Time value of money, Net present valuation, Socio-Economic impact analysis, Structural reliability theory. Monte Carlo Simulation techniques applied to investments, maintenance schedules formulation, repair intervention cycle determination in conjunction with end of life prediction. User cost estimation and evaluation of benefits to whole region.
Efficiency of Rehabilitation Interventions	Structural Reliability theory, Limit state function theory, Evaluation of reliability index to determine the efficiency. Bayesian decision theory in combination with Markov Deterioration modelling applied to optimisation theories. All techniques used in LCCA.
Risk and Vulnerability Analysis of Bridges	Probabilistic risk assessment, MCDM techniques, Fragility analysis, Monte Carlo techniques, Deterioration modelling techniques, Structural analysis techniques, Limit state function theory, material science principles. Machine learning approach to Artificial Intelligence. Weighted Multi factor modelling techniques, [Index based methods], Fuzzy and logic theories, Probabilistic theories, Fuzzy Analytical Hierarchy process techniques, Resilience assessment techniques, FEM, Decision making processes, Structural mechanic theories, Geo-Hazard integration with structural analysis.
Short Term Structural Health Monitoring	Vibration based monitoring by Modal Analysis theory. Operational Modal Analysis, Stochastic theory to estimate deterioration, Bayesian theory. Frequency domain decomposition techniques, data based anomaly detection technique, Time series analysis applied with statistical tools. FEM and structural mechanics theories. Machine learning applied AI tools.
Multi Criteria Decision Making Process to Bridge Resilience System	Value of money theories, Multi Attribute Utility theory, Fuzzy theory, Bayesian decision theory, Value engineering techniques. Analytical Hierarchy Process [AHP], Multi Attribute Utility Theory [MAUT], Fuzzy- AHP, Technique for Order of Preference by Similarity to Ideal Solution [TOPSIS], Data Envelopment Technique. Hybrid MCDM modeling using Fuzzy AHP. Allocation of KPI [Weight assignment to performance

	indicator or main attributes in MCDM].
DELIVERABLES FROM BRIDGE RESILIENCE SYSTEM	
Data collection, acquisition and processing.	Entire database of all bridges captured and stored over years when Inspection is carried out. Provides historical narrative for all variable functionalities of BRS.
Bridge Deterioration modelling, Balance Service life, Absolute Balance Service life and Median Service life	Provides important results that conventional Bridge Management System provides but based on age of bridge. Median Service Life evaluation enables probability estimation of the efficiency of rehabilitation interventions. Provides a **Proactive approach to BMS**. Application of Machine learning and Artificial Learning tools enable BRS to provide predictive maintenance scenarios that enhance the resilience of the bridge.
Risk and Vulnerability Analysis of Bridges	Provides results for the most important parameter of Enhancing Resilience in bridge by determination of vulnerability and resultant risk the bridge faces for four main natural hazards that result in Bridge failure. Also provides a probability of bridge survival scenario for the four natural hazards based on structural status of the bridge and the severity of natural hazard occurrence. Machine learning and Artificial Learning tools enable BRS to link the past occurrence of natural hazards and predict the behaviour of the bridge if similar events were to occur in future. This behaviour dictates the multi dimensional estimation of Risk and Vulnerability.
Multi Criteria Decision Making Process to Bridge Resilience System	Provides a Proactive approach and financial logic to fund allocation and fund optimisation by determination of bridge that should be provided funds and those that do not provide financial benefits to warrant fund allocation. System provides a sound financial due diligence during fund optimisation.

12. Conclusions

India is no exception to the fact that urbanization is engulfing the world. Urbanization results in rapid degradation of livability. Urban livability need to be adopted as a central objective of sustainable urban development and infrastructure planning. Rapid urbanization overwhelms infrastructure capacity. Logistic networks constitutes a key component of Infrastructure; with bridges contributing immensely. Bridges constitute an indispensable lifelines for modern societies. They accord seamless connectivity, sustains commerce, and fosters social and economic development. They link towns and cities, ensuring efficient movement of the population, goods and services. Beyond economic contributions, bridges play a pivotal role during emergencies. Bridges are long-life structures designed to perform safely and reliably for 50 to 100 years of service. Like all man-made structures, bridges inevitably age and deteriorate. While routine wear and tear may manifest as visible signs, much of the distress often progresses silently until significant damage occurs. Traditionally, bridge management has a reactive approach to rehabilitation. This approach, exposes infrastructure and communities to heightened risks. In contrast, a proactive approach focuses on early detection of vulnerabilities, accurate estimation of forces acting on bridge structures, and timely implementation of rehabilitation or strengthening strategies to extend service life and enhance resilience. The urgency of adopting proactive bridge management is amplified by the increasing frequency and severity of natural hazards such as floods, earthquakes, cyclones, and landslides. Research gaps provided the motivation for developing a Multi-Hazard Bridge Resilience Decision Support Framework. Bridge Resilience System offer comprehensive solutions to these challenges. BRS enables systematic quantification of hazard exposure, deterioration, and vulnerability, also incorporating Multi-Criteria Decision-Making [MCDM] to balance structural, financial, socio-economic, and functional priorities.

Multi-Criteria Decision Making [MCDM] enhances decision-making by utilizing multiple criterion. The four criterion adopted with MCDM are Structural status, Risk assessment, Financial due diligence, and Socio-economic impact. Criteria prioritization includes safety, structural integrity, operational efficiency, resilience against natural disasters, and socio-economic impacts like economic benefits and community advantages.

Bridge infrastructure is fundamental to transportation continuity, economic activity, emergency response, and social connectivity. Ageing and progressive deterioration, combined with exposure to challenging natural hazards, create a need for bridge-management practices that look beyond present condition.

The expanded analysis demonstrates that bridge risk is influenced by the interaction of deterioration, hazard exposure, structural vulnerability, functional importance, network criticality, socio-economic consequence, and financial feasibility. A condition-based approach remains essential but is insufficient when used in isolation.

The Bridge Resilience System provides an integrated pathway that connects bridge inventory, inspection, multi-hazard assessment, vulnerability analysis, risk evaluation, survival-related assessment, MCDM, lifecycle cost, financial due diligence, intervention planning, and monitoring. This integration supports a transition from reactive maintenance toward proactive resilience management.

The Kolhapur pilot demonstrates the practical relevance of this approach. Flooding emerges as the dominant recurring hazard, while landslides and seismic exposure contribute additional vulnerability. Selected bridges exhibit severe conditions and different survival-related characteristics, demonstrating the need for differentiated intervention priorities. The reported benefit–cost results further support the economic relevance of resilience investment.

The long-term objective of BRS is not to eliminate every possible risk, which is neither technically nor financially realistic. Its objective is to identify unacceptable risk early, protect essential connectivity, optimize limited resources, strengthen vulnerable bridges, prepare for disruption, and improve recovery. In this sense, BRS provides a foundation for sustainable logistic infrastructure in which bridge resilience becomes an integral component of infrastructure planning rather than a response after failure.

BRS is proposed as an integrated digital decision-support platform for managing bridge infrastructure under multi-hazard conditions. Unlike conventional bridge management systems that primarily focus on inspections and maintenance, the BRS combines bridge inventory, condition assessment, hazard analysis, vulnerability evaluation, resilience assessment, rehabilitation planning, financial analysis, and decision support within a unified framework. Risk is the probability of a hazardous event occurring combined with the consequences that follow. Vulnerability is the inherent weaknesses within the bridge system that make it more susceptible to damage when exposed to hazards. The critical implication of deterioration begins from day one of service and continues as the bridge ages, making older bridges significantly more prone to distress and failure. As deterioration progresses, the bridge's effective load-carrying capacity gradually reduces. This reduction not only compromises the safety and durability of the structure but also leads to decreased performance, affecting serviceability, reliability, and resilience against hazards. Unattended over time, deterioration can escalate to severe structural failures, causing disruptions to connectivity and posing risks to public safety.

Ageing bridges present a unique challenge in risk and vulnerability evaluation because their performance decreases steadily over time, while hazard intensity and frequency are increasing due to climate change. Globally all existing bridges show propagating distress. This degree of distress is dependent upon the age of bridge, geospatial location, and exposure to environment. When one has to evaluate the consequence of natural hazards on existing bridges, it is critical to have clarity on how the forces of natural hazards will act on pre-existing deterioration model. This makes it essential to model varying deterioration stages and impose the force of natural hazard on the deteriorated bridge structure. Results enabled define the consequences of the natural hazard on the bridge structure.

BRS fulfills all the key requirements of Bridge Management and offer analytical evaluation to include the results from Life Cycle Cost analysis, Risk and

Vulnerability analysis. Using Multi-Hazard analysis it also provides for most of the decision-making matrix to define which bridges need enhancement in resilience. Further to optimize the fund allocation, BRS applies the Multi-Criteria Decision-making protocol. This provides the user with financial due diligence and justification to seek budgetary support by definition of cost-benefit rational.

Conflict of Interest: The authors declare no conflict of interest

Funding: NA

Data Availability: All the data has been sourced from our research and research documents are available on https://ubmsresearchgroup.com and https://bridgeresiliencesystem.com

Acknowledgments

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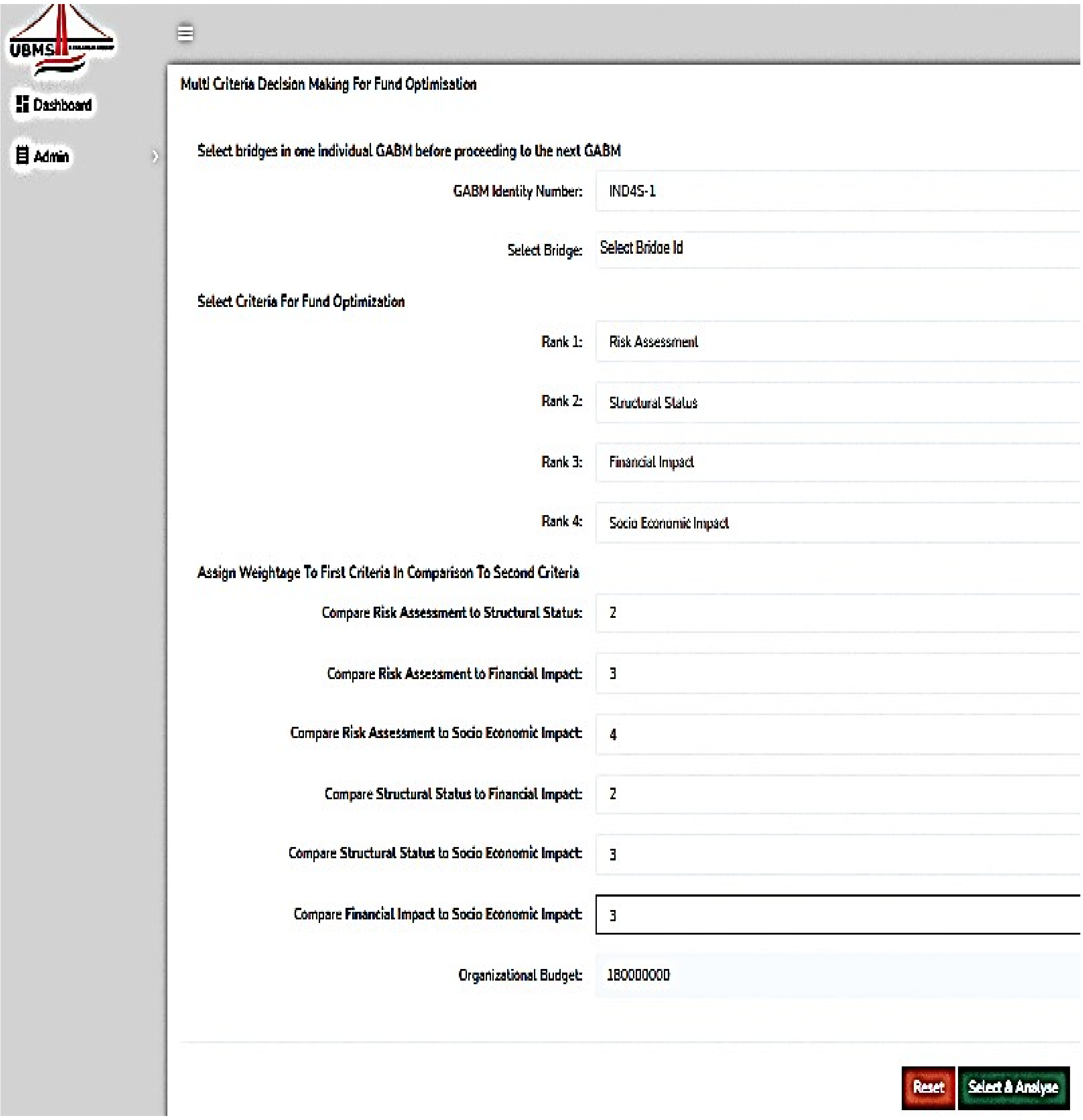
Annexure A


UBMS
Dashboard
Admin
Multi Criteria Decision Making For Fund Optimisation
Select bridges in one individual GABM before proceeding to the next GABM
GABM Identity Number: IND4S-1
Select Bridge: Select Bridge Id
Select Criteria For Fund Optimization
Rank 1: Risk Assessment
Rank 2: Structural Status
Rank 3: Financial Impact
Rank 4: Socio Economic Impact
Assign Weightage To First Criteria In Comparison To Second Criteria
Compare Risk Assessment to Structural Status: 2
Compare Risk Assessment to Financial Impact: 3
Compare Risk Assessment to Socio Economic Impact: 4
Compare Structural Status to Financial Impact: 2
Compare Structural Status to Socio Economic Impact: 3
Compare Financial Impact to Socio Economic Impact: 3
Organizational Budget: 180000000
Reset
Select & Analyse

RESULTS FOR FUND OPTIMIZATION POST APPLICATION OF MULTI-CRITERIA DECISION-MAKING PROCESSES

Selected Bridge : 'NH0036B006', 'NH0038B007', 'NH0081B002', 'NH0016B007', 'NH0026B006', 'NH0516B002', 'NH0044B002', 'NH044B007', 'NH0161B002', 'NH0060B006'

RESULT AS PER SIMPLE MULTI-ATTRIBUTE RATING TECHNIQUE [SMART]

RANK BRIDGES AND DETERMINE REHABILITATION POSSIBILITY

RANK OF THE BRIDGE	Bridge ID	Weighted Score	Rehabilitation Cost Estimated	Cumulative Cost	Rehabilitation Possible
1	NH0016B007	3.15	15,000,000.00	15,000,000.00	YES
2	NH0060B006	2.888	35,000,000.00	50,000,000.00	YES
3	NH044B007	2.6	40,000,000.00	90,000,000.00	YES
4	NH0038B007	2.6	15,000,000.00	105,000,000.00	YES
5	NH0516B002	2.485	20,000,000.00	125,000,000.00	YES
6	NH0161B002	2.45	25,000,000.00	150,000,000.00	YES
7	NH0026B006	2.425	9,500,000.00	159,500,000.00	YES
8	NH0081B002	2.32	20,000,000.00	179,500,000.00	YES
9	NH0036B006	2.313	9,500,000.00	189,000,000.00	NO
10	NH0044B002	2.25	19,000,000.00	208,000,000.00	NO

REFINEMENT AS PER ANALYTICAL HIERARCHY PROCESS (AHP)

ASSIGNMENT OF BUDGET FOR RI

ASSIGNED RANK	BRIDGE ID	ESTIMTED COST	ASSIGNED BUDGET
1	NH0016B007	15,000,000.00	13,500,000.00
2	NH0060B006	35,000,000.00	26,250,000.00
3	NH044B007	40,000,000.00	30,000,000.00
4	NH0038B007	15,000,000.00	11,250,000.00
5	NH0516B002	20,000,000.00	11,000,000.00
6	NH0161B002	25,000,000.00	13,750,000.00
7	NH0026B006	9,500,000.00	7,125,000.00
8	NH0081B002	20,000,000.00	11,000,000.00
9	NH0036B006	9,500,000.00	7,125,000.00
10	NH0044B002	19,000,000.00	10,450,000.00

FEASIBILITY OF ENHANCING BUDGET TO ENSURE STRUCTURAL AND RESILIENCE ADEQUACY(ALL FIGURES ARE IN MILLIONS)

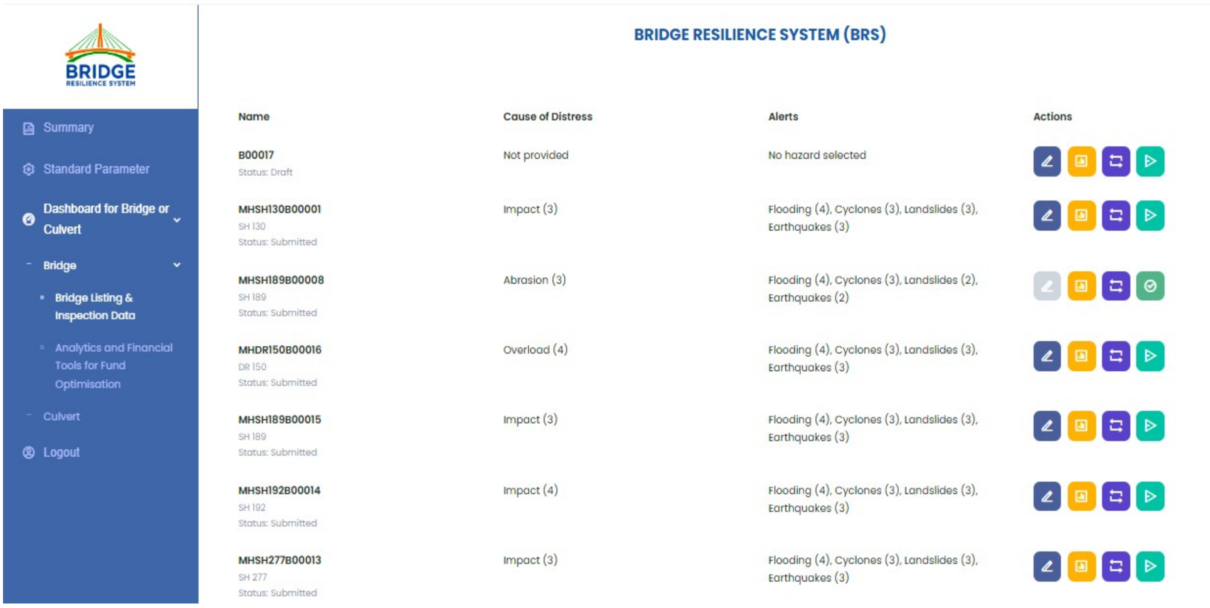
	Extra Budget essential (+)/ Excess budget available (-) FOR RESILIENCE AND STRUCTURAL ADEQUACY	Extra Budget essential (+)/ Excess budget available (-) FOR ONLY STRUCTURAL ADEQUACY	Extra Budget essential (+)/ Excess budget available (-) FOR ONLY RESILIENCE ADEQUACY	TOTAL BENEFITS ACCRUED DUE TO RESILIENCE AND STRUCTURAL ADEQUACY
TOTAL IMPACT FOR ALL BRIDGES	328.59	100.88	9.35	2,598.93

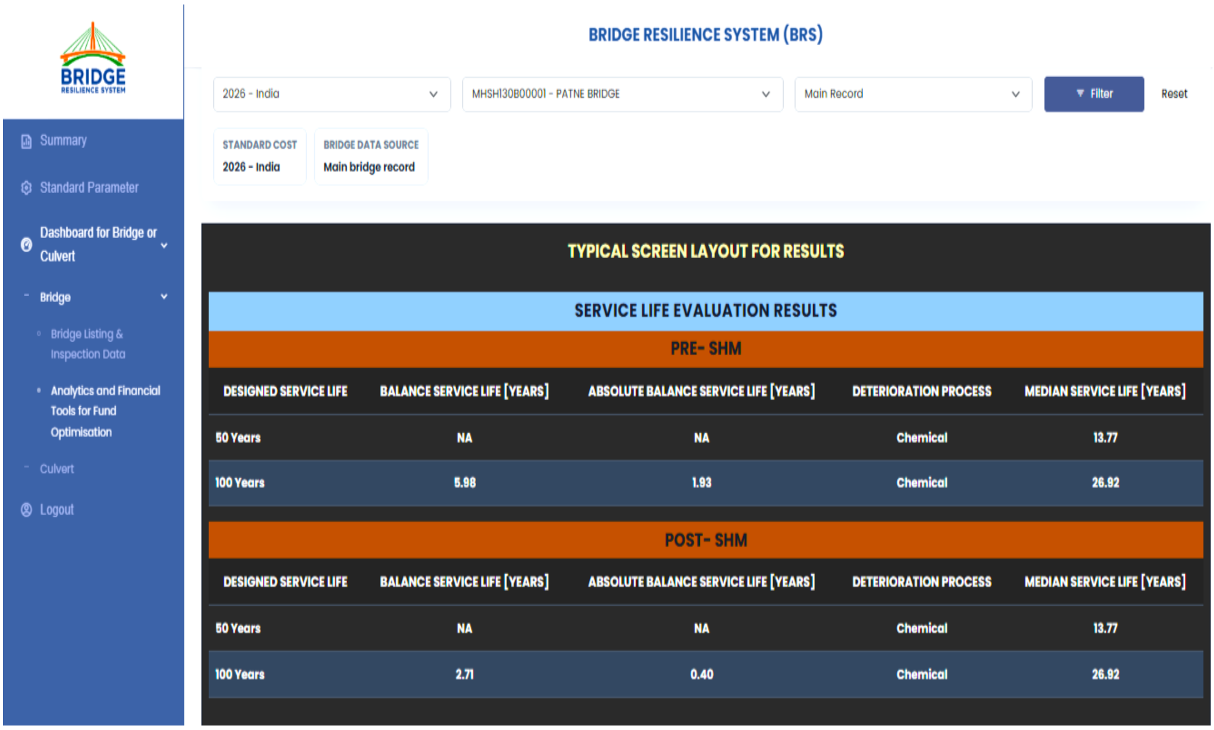
TOTAL BENEFITS ACCRUED CONSISTS OF:
a. Direct Benefit
b. Indirect Benefit

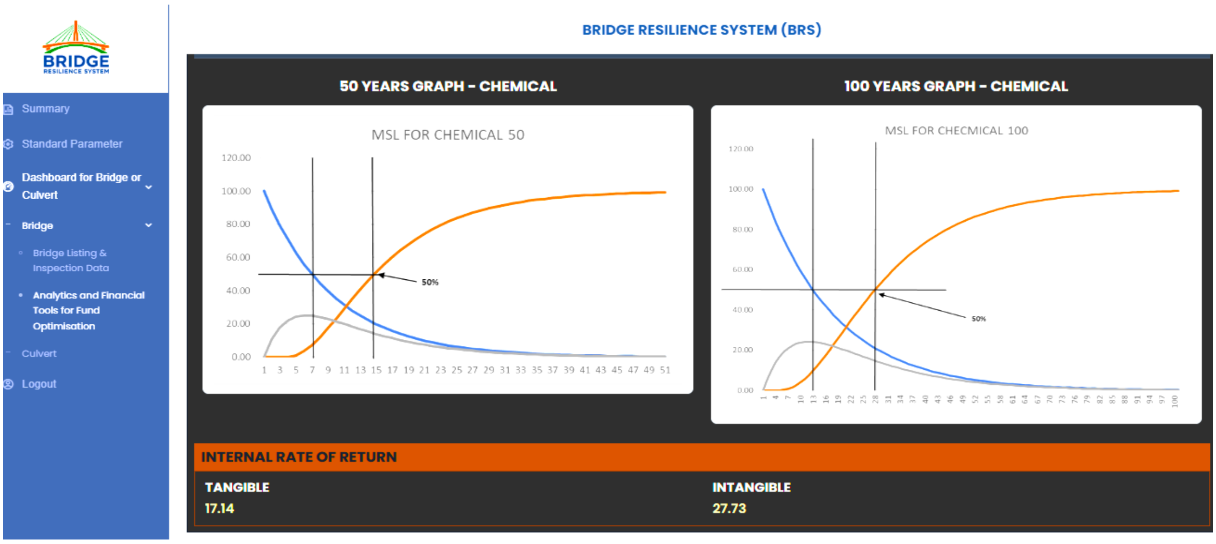
Direct Benefit consists of Savings in Vehicle Operating Cost (VOC) and Vehicle Operating Time (VOT) for the trip.

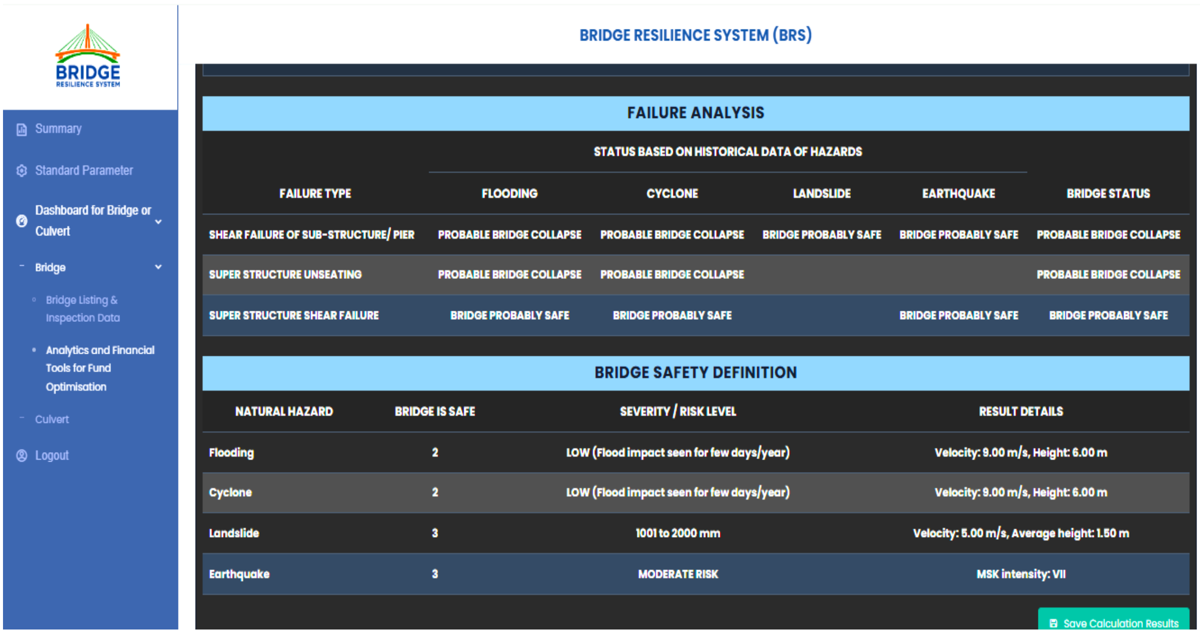
Indirect Benefit consists of Impact of Economic Growth Potential, Social Benefit accrued, Time saved due to reduction in distance and time because of the bridge and Environmental Impact. It evaluates the impact of the bridge on the regions GDP, increase in employment, productivity and social benefits due to ease of connectivity to schools, hospitals, place of work, recreation.

Few results from BRS are shown herein-



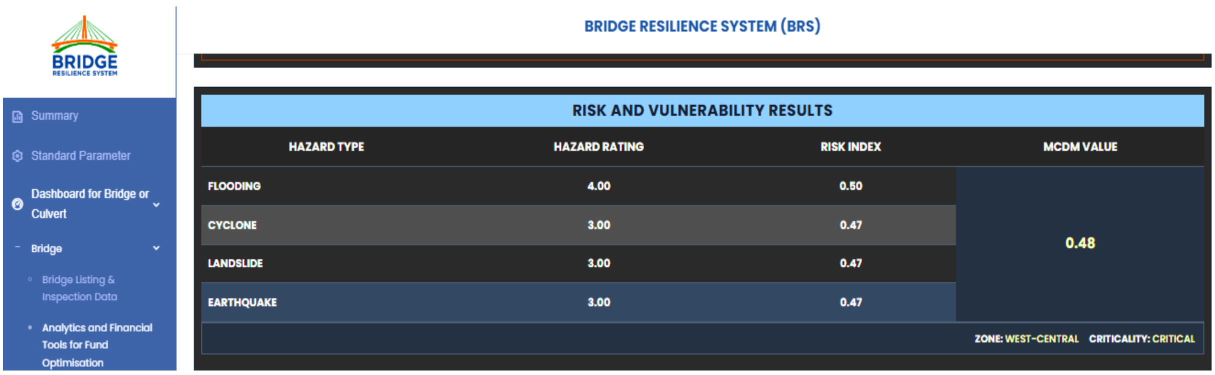




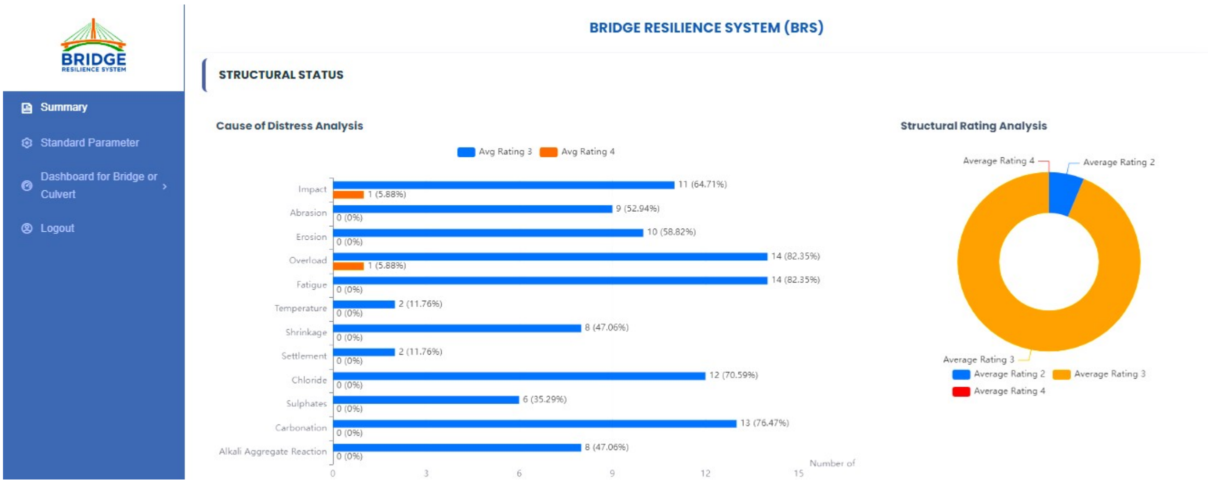


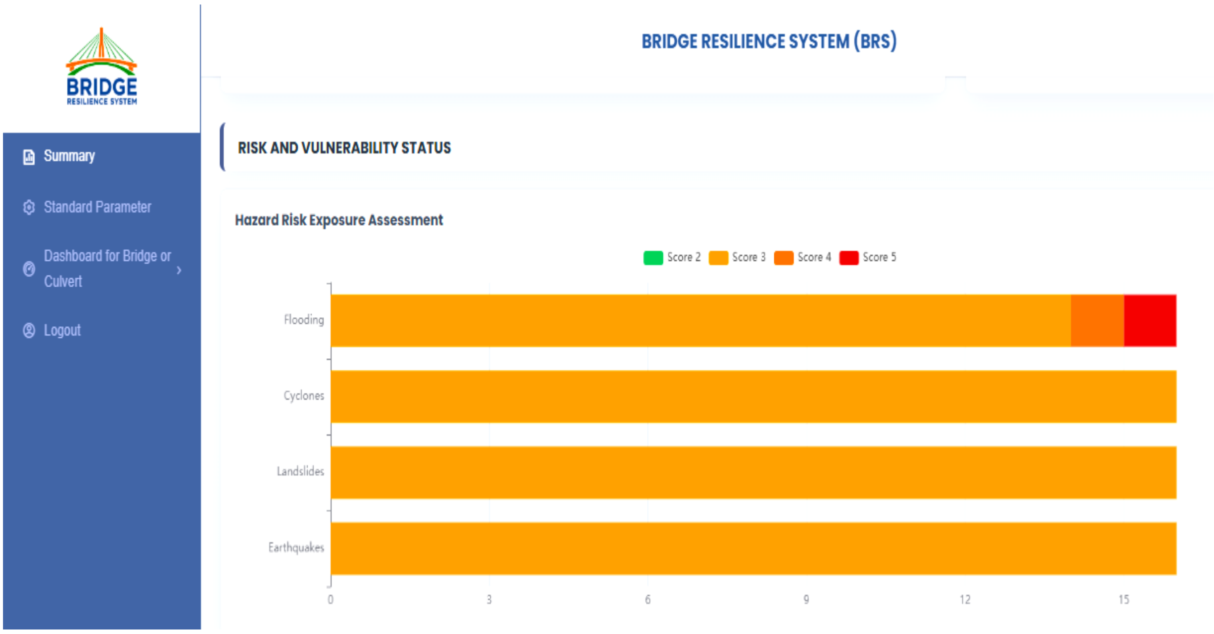
FAILURE TYPE	FLOODING	CYCLONE	LANDSLIDE	EARTHQUAKE	BRIDGE STATUS
	STATUS BASED ON HISTORICAL DATA OF HAZARDS				
SHEAR FAILURE OF SUB-STRUCTURE/ PIER	PROBABLE BRIDGE COLLAPSE	PROBABLE BRIDGE COLLAPSE	BRIDGE PROBABLY SAFE	BRIDGE PROBABLY SAFE	PROBABLE BRIDGE COLLAPSE
SUPER STRUCTURE UNSEATING	PROBABLE BRIDGE COLLAPSE	PROBABLE BRIDGE COLLAPSE			PROBABLE BRIDGE COLLAPSE
SUPER STRUCTURE SHEAR FAILURE	BRIDGE PROBABLY SAFE	BRIDGE PROBABLY SAFE		BRIDGE PROBABLY SAFE	BRIDGE PROBABLY SAFE

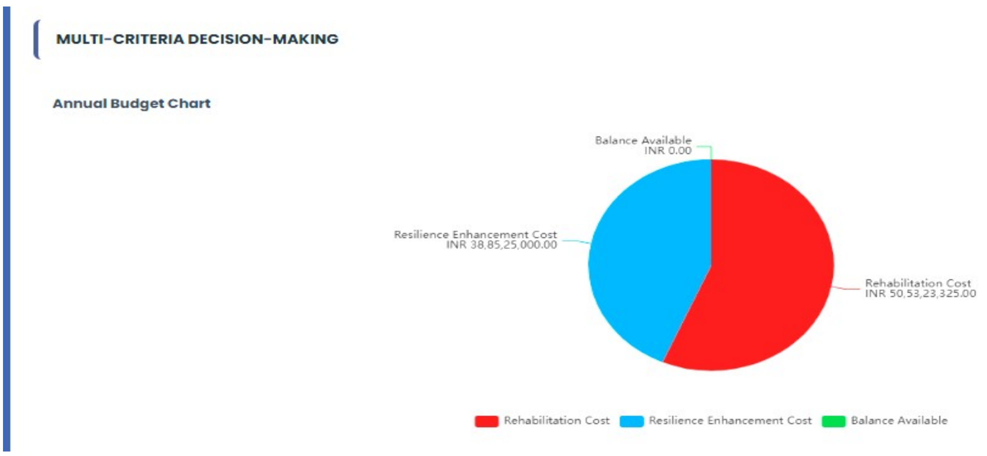
NATURAL HAZARD	BRIDGE IS SAFE	SEVERITY / RISK LEVEL	RESULT DETAILS
Flooding	2	LOW (Flood impact seen for few days/year)	Velocity: 9.00 m/s, Height: 6.00 m
Cyclone	2	LOW (Flood impact seen for few days/year)	Velocity: 9.00 m/s, Height: 6.00 m
Landslide	3	1001 to 2000 mm	Velocity: 5.00 m/s, Average height: 1.50 m
Earthquake	3	MODERATE RISK	MSK intensity: VII

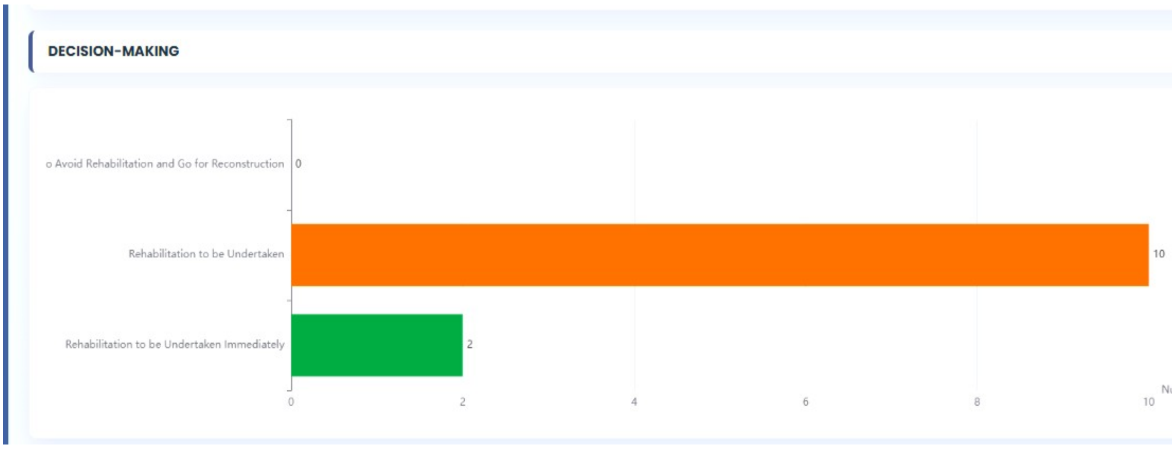


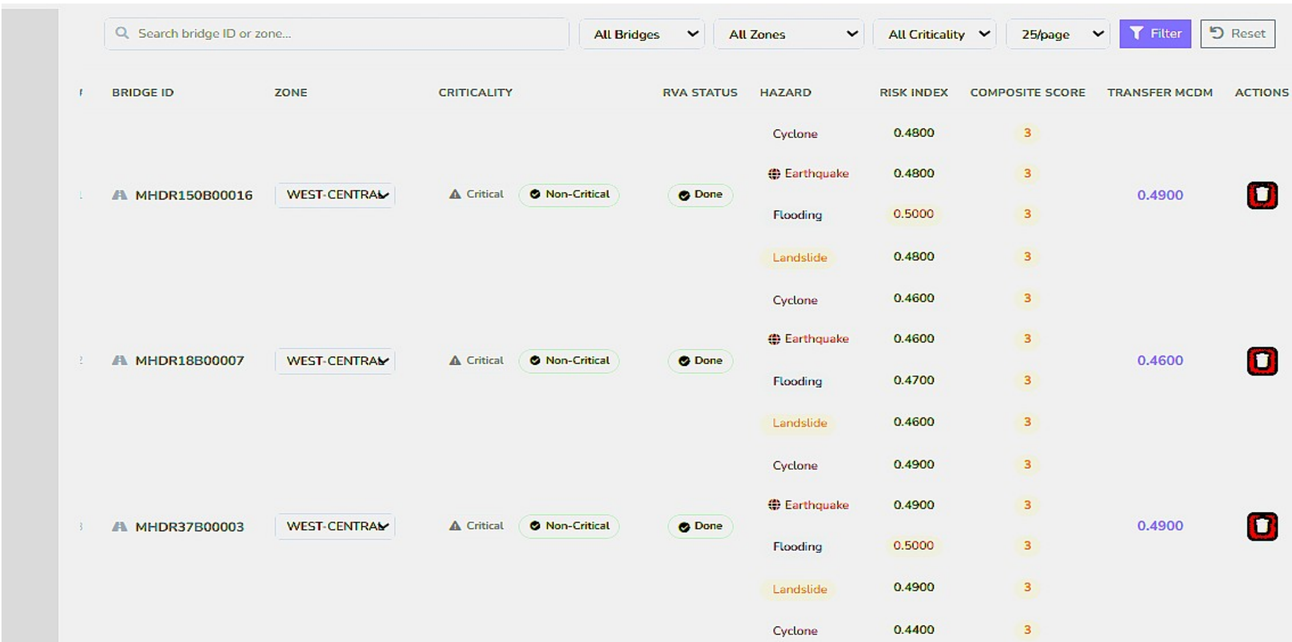
HAZARD TYPE	HAZARD RATING	RISK INDEX	MCDM VALUE
FLOODING	4.00	0.50	0.48
CYCLONE	3.00	0.47	
LANDSLIDE	3.00	0.47	
EARTHQUAKE	3.00	0.47	


BRIDGE
RESILIENCE SYSTEM
Summary
Standard Parameter
Dashboard for Bridge or Culvert
Logout
BRIDGE RESILIENCE SYSTEM (BRS)
STRUCTURAL STATUS
Cause of Distress Analysis
Avg Rating 3
Avg Rating 4
Impact
Abrasion
Erosion
Overload
Fatigue
Temperature
Shrinkage
Settlement
Chloride
Sulphates
Carbonation
Alkali Aggregate Reaction
11 (64.71%)
1 (5.88%)
9 (52.94%)
10 (58.82%)
14 (82.35%)
2 (11.76%)
8 (47.06%)
12 (70.59%)
6 (35.29%)
13 (76.47%)
0 (0%)
Number of
Structural Rating Analysis
Average Rating 4
Average Rating 2
Average Rating 3


BRIDGE
RESILIENCE SYSTEM
Summary
Standard Parameter
Dashboard for Bridge or Culvert
Logout
BRIDGE RESILIENCE SYSTEM (BRS)
RISK AND VULNERABILITY STATUS
Hazard Risk Exposure Assessment
Score 2
Score 3
Score 4
Score 5
Flooding
Cyclones
Landslides
Earthquakes
0
3
6
9
12
15


MULTI-CRITERIA DECISION-MAKING
Annual Budget Chart
Balance Available
INR 0.00
Resilience Enhancement Cost
INR 38,85,25,000.00
Rehabilitation Cost
INR 50,53,23,325.00
Rehabilitation Cost
Resilience Enhancement Cost
Balance Available





Search bridge ID or zone...
All Bridges
All Zones
All Criticality
25/page
Filter
Reset

BRIDGE ID	ZONE	CRITICALITY	RVA STATUS	HAZARD	RISK INDEX	COMPOSITE SCORE	TRANSFER MCDM	ACTIONS
MHDR150B00016	WEST-CENTRAL	Critical / Non-Critical	Done	Cyclone	0.4800	3	0.4900	
				Earthquake	0.4800	3		
				Flooding	0.5000	3		
				Landslide	0.4800	3		
MHDR18B00007	WEST-CENTRAL	Critical / Non-Critical	Done	Cyclone	0.4600	3	0.4600	
				Earthquake	0.4600	3		
				Flooding	0.4700	3		
				Landslide	0.4600	3		
MHDR37B00003	WEST-CENTRAL	Critical / Non-Critical	Done	Cyclone	0.4900	3	0.4900	
				Earthquake	0.4900	3		
				Flooding	0.5000	3		
				Landslide	0.4900	3		
				Cyclone	0.4400	3		

SL. No.	GABM ID	Bridge ID	Age (yrs)	Principal Cause	EC Value	FR (Years)	AF Value	Conclusion
1	IND-02	MHSH192B00014	54	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN
2	IND-02	MHSH192B00002	69	Mechanical	0.40	5.00	0.3900	REHABILITATION TO BE UNDERTAKEN
3	IND-02	MHSH192B00012	59	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN
4	IND-02	MHSH189B00015	58	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN
5	IND-02	MHSH189B00008	49	Mechanical	0.65	6.00	0.3630	REHABILITATION TO BE UNDERTAKEN
6	IND-02	MHSH166B00006	90	Mechanical	0.40	5.00	0.4830	REHABILITATION TO BE UNDERTAKEN
7	IND-02	MHDR53B00011	55	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN
8	IND-02	MHDR53B00004	55	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN
9	IND-02	MHDR39B00005	24	Chemical	0.60	6.00	0.2940	REHABILITATION TO BE UNDERTAKEN IMMEDIATELY
10	IND-02	MHDR37B00003	55	Mechanical	0.65	6.00	0.4230	REHABILITATION TO BE UNDERTAKEN
11	IND-02	MHDR18B00007	22	Chemical	0.60	6.00	0.2940	REHABILITATION TO BE UNDERTAKEN IMMEDIATELY
12	IND-02	MHDR150B00016	50	Mechanical	0.65	6.00	0.3900	REHABILITATION TO BE UNDERTAKEN

Showing 1 to 12 of 12 entries

Previous 1 Next

PART C:

BRIDGE RESILIENCE PERFORMANCE INDEX[BRPI] AND NETWORK PERFORMANCE INDEX [NPI]

BRIDGE RESILIENCE PERFORMANCE INDEX[BRPI] AND NETWORK PERFORMANCE INDEX [NPI]

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Joshi Sachidanand; Head Mentor : UBMS Research Group. Orcid: 0000-0002-3787-1884
Menon Sreenath: Researchers: UBMS Research Group, Orcid: 0009-0002-8941-0462

Abstract:

Bridge Resilience Performance Index [BRPI] clubbed with Network Performance Index [NPI] provides critical information relating to the overall performance of the bridge and the network to fulfill the task during crucial time. BRPI and NPI provide the confidence on the performance of bridge and network to perform in future should a severe natural hazard occur. They quantify the bridge performance within the whole network. Bridge Resilience System [BRS] aims to define the optimisation of fund allocation, BRPI within BRS provides the user to define strategics that could enable them fulfillment of performance goals. Such a process also enhances the quality control system. Comparison of performance goals achieved with the targeted performance goals provides that key input which indicates success of quality control mechanism. The users of BRS could then decide to use BRPI as the main parameter to dictate the prioritization of fund allocation or re-evaluate the bridge priority list provided by BRS using the MCDM technique.

This paper provides a brief summary of the objectives of evaluation of performance index, and provides the road map to implementation methodology.

1. Define the objective of the Performance Index

The first step is to establish the purpose of the Bridge Resilience Performance Index [BRPI] within BRS. The BRPI provides a single overall representation of the performance of an individual bridge. The key parameters considered are:

1. Structural condition
2. Functional importance
3. Safety and reliability
4. Vulnerability and risk
5. Socio-economic importance
6. Financial condition
7. Robustness
8. Maintainability.

The purpose is not simply to identify whether a bridge is structurally good or bad. The index integrates various other critical parameters including the Vulnerability and Risk Index of the bridge. BRPI provides a broader understanding of how well the bridge is performing and whether it requires inspection, maintenance, rehabilitation, strengthening, or other intervention.

2. Create the Bridge Performance Assessment record

For every bridge in BRS, the system creates a dedicated Resilience Performance Index assessment record. The assessment is linked to the unique **Bridge ID** so that all information required for the index can be retrieved automatically from the existing BRS database.

The system collects the latest available information for the bridge, while also maintaining the assessment date and historical values. This is important because the Resilience Performance Index should be capable of showing whether a bridge's performance is improving, deteriorating, or remaining stable over time. The basic structure should therefore be:

Bridge ID → Existing BRS Data → Individual Resilience Performance Indicators → Overall Resilience Performance Index.

3. Collect structural performance information

The first major component is the **structural performance of the bridge.** BRS obtains information from the structural assessment and inspection modules. This include the condition of major bridge components such as the deck, superstructure, substructure, bearings, joints, foundations and other relevant components.

The system uses the latest inspection and structural assessment results rather than requiring the user to enter the same information again. The structural assessment identify the present condition of the bridge and whether any component has significant deterioration or structural deficiency. This information becomes the foundation for evaluating the bridge's overall physical performance.

4. Assess load-carrying performance

The next step is to determine whether the bridge is capable of safely carrying the loads expected during its operation. BRS obtains the bridge's design load or original capacity information from the structural inventory and compare it with the current loading demand obtained from traffic and structural assessment information. The system then considers the actual traffic environment, including normal traffic and, where available, heavy-vehicle traffic. The purpose of this stage is to identify whether the bridge has sufficient capacity or whether its available capacity is becoming a concern. The output is Load-Capacity Performance indicator that can be passed automatically to the overall BRPI calculation.

5. Incorporate traffic information

Traffic is an important functional parameter for Resilience Performance Index. BRS has information relating to ADT/AADT for every bridge. Where available, the system maintains vehicle classification and heavy-vehicle information. The traffic value should preferably come from an existing traffic database, traffic survey, authority records, or another validated source.

The BRS system stores the traffic value but also associate it with the bridge's functional importance. A bridge carrying very high traffic has a different performance implication from a bridge carrying very low traffic, even when their structural conditions are similar. The integrated traffic information is passed to the functional and network-related components of the Resilience Performance Index.

6. Assess road and functional importance

The bridge's road category is identified, such as National Highway, State Highway, Major District Road, or other relevant classification. The road category provides an indication of how strategically important the bridge is to transportation.

For example, failure of a bridge on a major national route can have considerably greater consequences than failure of a bridge on a low-volume local road. BRS therefore retrieves the road classification from the bridge inventory or transportation network database and use it as part of the bridge's functional performance assessment.

7. Determine reliability performance

The next component evaluated is **reliability**.

BRS obtains the reliability assessment results from the structural/reliability analysis module. The objective is to determine how confidently the bridge can perform its intended function under the expected loading and environmental conditions. Where reliability analysis is available, BRS stores the resulting reliability measure and the corresponding performance classification.

If reliability information is not available for a particular bridge, the system identifies it as a data gap rather than automatically assigning a favorable score.

8. Assess vulnerability

The vulnerability component comes from the BRS Risk and Vulnerability Assessment. The system considers the bridge's susceptibility to relevant hazards such as flooding, earthquakes, landslides, scour, cyclones, extreme weather, or other hazards applicable to its location.

BRS combines the available hazard exposure and bridge vulnerability information to determine how susceptible the bridge is to damage or loss of functionality. The vulnerability result is then passed directly to the Resilience Performance Index.

9. Incorporate Risk Index

The Risk Index is obtained from the existing BRS risk assessment module. Risk represents the combined understanding of hazard, vulnerability and consequence. The Resilience Performance Index uses the latest approved Risk Index for the bridge. If the risk assessment is updated, the BRPI is capable of being automatically updated. This creates an important connection between the existing BRS risk module and the new Resilience Performance Index.

10. Assess socio-economic importance

The next stage is to determine the socio-economic importance of the bridge. The BRS considers the role of the bridge in supporting:

- Population movement
- Local communities
- Industrial areas
- Commercial activities
- Agriculture
- Tourism
- Freight movement
- Economic activity
- Essential services

The objective is to understand the consequences of poor bridge performance from a social and economic perspective rather than looking only at engineering condition.

11. Assess emergency and accessibility importance

Where information is available, BRS identifies if the bridge provides access to critical facilities like hospitals, fire stations, police stations, emergency response facilities, evacuation routes and disaster shelters. If the bridge is on an important emergency access route, its performance should receive additional significance. This is especially valuable for the BRS because it connects the Resilience Performance Index with the broader concept of bridge resilience.

12. Assess financial performance

The next component is the financial aspect of bridge management. BRS obtains available information regarding inspection costs, maintenance costs, resilience enhancement costs, rehabilitation costs and potential reconstruction costs.

The system also considers the economic benefit or value associated with keeping the bridge operational. The purpose is not simply to identify the cheapest intervention. Instead, the financial assessment helps to determine whether continued maintenance, rehabilitation, strengthening or replacement is economically appropriate. The existing BRS financial/LCCA functionality therefore provide the required information for this part of the Resilience Performance Index.

14. Assess maintainability

The maintainability component represents how easily the bridge can be inspected, maintained, repaired and returned to service.

BRS should consider information such as:

- Current bridge age
- Remaining service life
- Design life
- Maintenance history
- Previous interventions
- Repair requirements
- Accessibility for maintenance
- Expected closure duration
- Difficulty of rehabilitation

This information can largely be obtained from the existing BRS service-life and maintenance modules. It evaluates the availability ratio of the bridge based on historical evidence. A bridge that requires frequent intervention or has very limited remaining service life shows poorer maintainability performance.

15. Determine the individual performance indicators

Once the above information has been collected, BRS creates individual performance indicators. The indicators should represent the major dimensions of bridge resilience performance rather than immediately producing one final number.

For example, BRS displays:

- Structural Performance
- Load-Capacity Performance
- Traffic/Functional Performance
- Reliability Performance
- Vulnerability Performance
- Risk Performance
- Socio-Economic Performance
- Financial Performance
- Robustness Performance
- Maintainability Performance

This information is very important because it allows an engineer to understand why a bridge has received its final Resilience Performance Index.