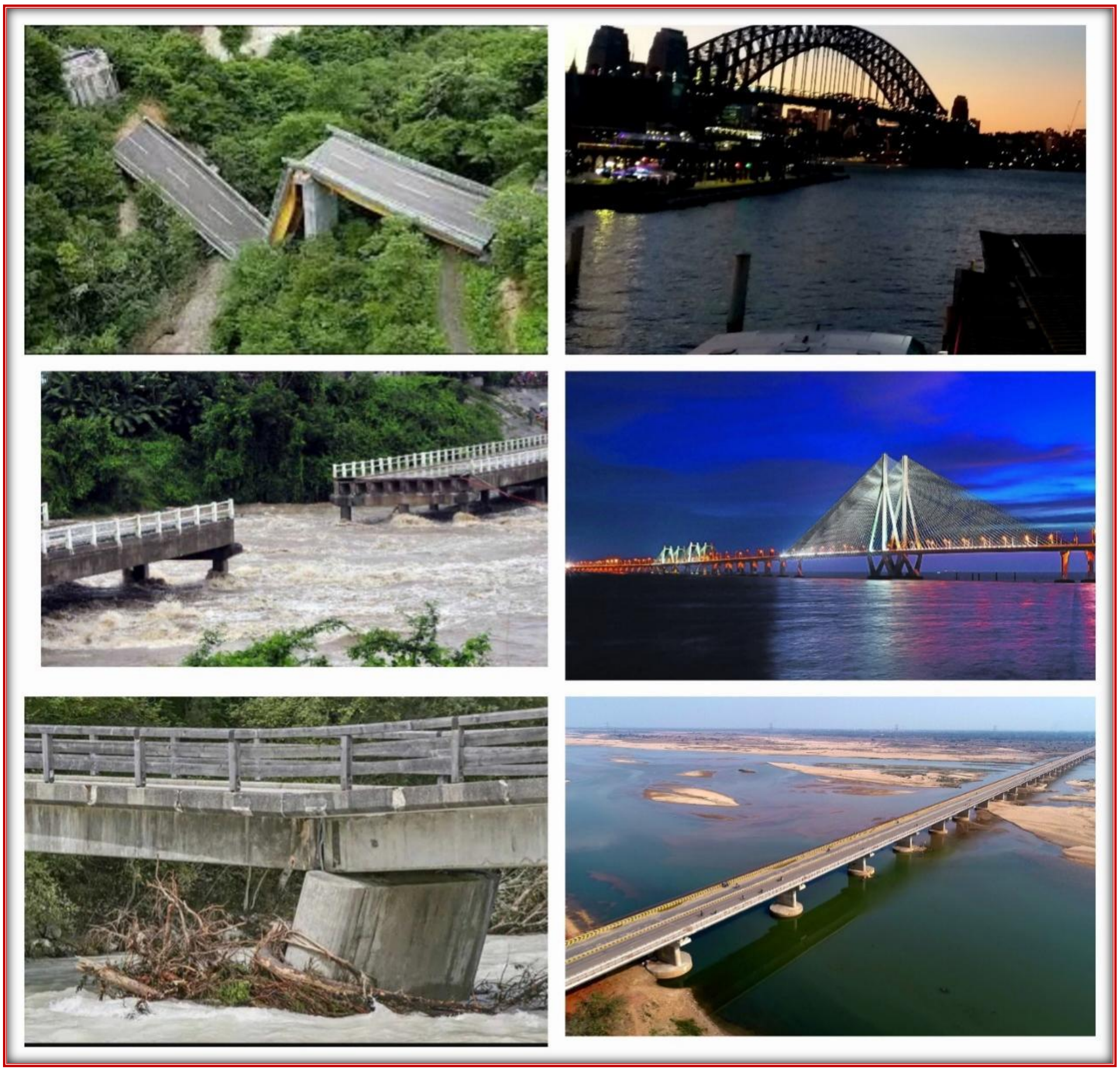

Integrating MCDM to Enhance Bridge Resilience

RESEARCHED AND CONCEPT
BY

UBMS RESEARCH GROUP

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Integrating MCDM to Enhance Bridge Resilience

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Integrating MCDM to Enhance Bridge Resilience

By: Sachidanand Joshi, Mayuri Tundalwar [Researchers; UBMS Research Group]

ABSTRACT:

Natural hazards occurrences show dynamism in terms of its frequency and severity. Entire world witnesses such dynamism. This has caught the engineering fraternity surprised and unprepared. Infrastructure endures the most of this dynamism. Designs of infrastructure and bridges in particular, do account for normal forces of natural hazards. Geographical vulnerability dictate the design practices. Dynamism results in negating assumptions of severity and frequency. The incremental forces influence structures, triggering an exponential deterioration process.

Global surge in infrastructure construction demands economical solutions. The concept of "Design and Built" adopted select the most economical design. Absence of stringent resilience requirements compromise long-term survival possibilities. Resilient bridges show a higher probability of survival.

Research explores possible approach to enhance resilience in bridges. It defines the boundaries for the bridge geometry and distress levels that will need to be adhered for ensuring survival of the bridge. *Bridge Management* [BM] has historically depended on a single criterion—the severity of structural deterioration—to make critical decisions about *Maintenance, Rehabilitation, Strengthening, or Replacement* [MRSR] of bridges. The sole criterion for ranking the bridge is the severity of deterioration within the bridge structure. This mono-criterion approach, while straightforward, focuses solely on the physical condition of the bridge, often neglecting other significant factors that might influence the decision-making process. Need was felt to have a Multi-Criteria Decision-Making [MCDM] process which would refocus on multiple criterion's. Research identified four criterion's namely Structural status of bridge structure, Risk assessment for natural hazards, Financial due-diligence, and Socio-Economic impact of the bridge on the region. MCDM integration holds the key to enhance resilience of bridges.

KEYWORDS: Resilience, Natural hazard, Bridge collapses, Dynamism, MCDM

1: INTRODUCTION

The growing intensity of natural hazards due to climate change has created unprecedented challenges for global infrastructure systems[1]. As natural disasters—floods, cyclones, landslides, and earthquakes—become increasingly frequent and severe, the resilience of infrastructure, especially bridges, becomes a crucial concern. Bridges, which are the lifeline of transportation and trade, are essential to the nation's socio-economic development. Bridges face augmented vulnerability under the dynamic forces of natural hazards. This changing landscape calls for an urgent reassessment of how we design, built, and maintain our bridges, to withstand future dynamic climatic threats. The research has global applicability. **Focus is on India** to enable design the approach and methodology.

India like every other region in the world, show diverse geographical and climatic conditions, exposing infrastructure to a wide spectrum of natural hazards. States in the north and eastern regions are prone to high seismic activity and flooding. States in the southern and west central regions are prone to floods and cyclones. Despite the critical role bridges play, the design practices used in their creation often rely on historical data, which fail to account for the growing intensity and unpredictability of natural disasters. Resilient bridges becomes a pivotal issue in ensuring long-term safety and functionality of logistics network in the face of rapid urbanization and an increasing infrastructure demand.

Bridge Management [BM] has historically depended on a single criterion—the severity of structural deterioration—to make critical decisions about *Maintenance, Rehabilitation, Strengthening, or Replacement* [MRSR] of bridges. The sole criterion for ranking the bridge is the severity of deterioration within the bridge structure. This mono-criterion approach, while straightforward, focuses solely on the physical condition of the bridge, often neglecting other significant factors that might influence the decision-making process.

With the integration of *Life cycle cost analysis* [LCCA] with BM, the details of yearly benefits accrued to the users due to bridge are available. The integration of LCCA into BM introduces a broader perspective, providing detailed insights into the yearly benefits that bridges offer to users, encompassing both tangible and intangible benefits. Tangible benefits are quantifiable and directly measurable, such as reduced travel time and vehicle operating costs. Intangible benefits, often socio-economic in nature, include improved connectivity and economic development in the region. Incorporating these benefits into LCCA enabled a more comprehensive evaluation of the net benefits that a bridge provides over its lifetime. This brought a new dimension in decision-making.

The Socio-Economic parameter provided a framework to evaluate the unseen or intangible benefits that the existence of the bridge brings into the region. Clubbing these intangible benefits into LCCA, enabled evaluation of the Net benefits, the bridge accrues. Socio-Economic parameters also brought sufficient information relating to the impact of bridge on the regional social and economic development. In present day scenario, the economic growth is critical for every country. The uninterrupted logistics provided by transport network is critical for the economic growth and social stability. Various events of recent past have shown the impact of disruptions in logistics resulted in stalled growth and stability in many countries across the world. Transportation network are critical for the overall economic growth and social stability. Poor network or non-continuous networks cause impediments to growth and stability. This aspects form another critical dimension in BM.

UBMS Research Group [URG] submitted a Voluntary Commitment to Sendai Framework for Voluntary Commitment [SFVC] under United Nations office for Disaster Risk Reduction [UNDRR][2]. TO fulfil the given commitment, URG evolved the *Global Analytics for Bridge Management* [GABM] and *Global Analytics for Risk and Resilience Management* [GARM]. These tools offer critical information on the risks faced by bridges and their resilience to natural hazards like earthquakes, flooding, cyclones, and landslides. They also provide data on the probability of bridge survival post-disaster, which is crucial for rescue and relief operations. GABM and GARM provide critical information about the Risks to the bridge and associated Resilience of the bridge under various Natural Hazards. Availability of this risk and arising need for resilience brought the fourth dimension to Decision-making in Bridge Management.

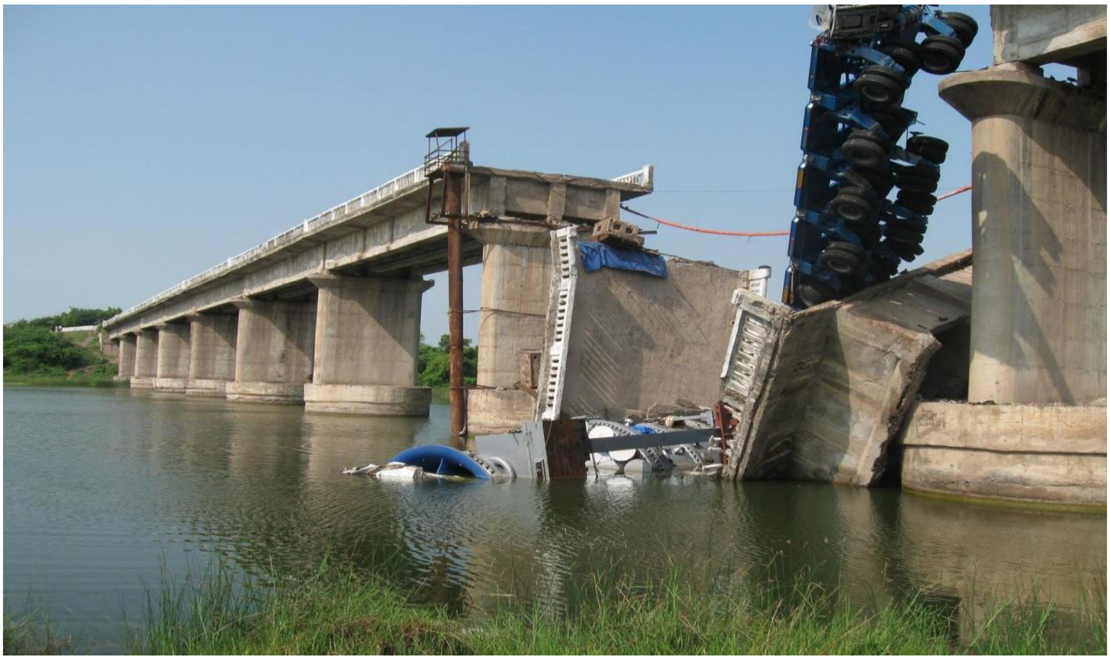


Image Credit 01: pixabay.com/photos/bridge-collapse-damage-312873/(Talaja Bridge)

With all the above information available in BM, decision-making becomes a very complex process. *Multi Criteria Analysis* [MCA] provides a comprehensive solution to resolve the complications of decision-making. It also is possible to ensure flexibility and transparency in decision-making processes. All these properties render MCA open to debating on the approach taken to make the decision.

Given the complexity of modern BM, Multi-Criteria Analysis (MCA) emerges as a robust solution to streamline decision-making. MCA facilitates the inclusion of multiple criteria, ensuring that decisions are flexible, transparent, and open to scrutiny. This method allows for a structured analysis that incorporates various factors, including:

- Structural status of bridges
- Financial implications (both tangible and intangible)
- Socio-economic parameters resulting from bridge usage
- Impact of natural hazards on the bridge

MCA's structured approach ensures logical consistency, transparency, and ease of use. It allows decision-makers to incorporate judgment and accountability into the process, without differentiating between the welfare and sufferings that an action may cause.

The ultimate goal in BM is to apply judicious logic to decide on MRSR actions. However, the availability of funds often restricts the application of MRSR, necessitating a selection procedure to prioritize bridges. In regions, where *Disaster Risk Reduction* [DRR] funds are limited, it becomes critical to maintain high resilience levels for bridges on certain pre-decided routes. MCA introduces an element of order to this selection procedure, helping systematically to prioritize bridges based on multiple criteria, rather than solely on their structural condition.

MCA brings significant advantages to bridge management decision-making by ensuring:

- Comprehensive consideration of all relevant factors
- Transparency and accountability
- Logical and consistent analysis
- Flexibility and adaptability in decision-making processes

By incorporating MCA, bridge management can evolve from a mono-criterion approach to a more holistic, multi-faceted decision-making framework that better addresses the complexities of modern infrastructure management.

Formal MCA methods are either continuous or discrete methods. Continuous methods, such as linear programming, address problems with a large number of options, while discrete methods handle a limited set of alternatives. Discrete methods include full aggregation methods like *Multi-Attribute Utility Theory* [MAUT].

The mathematical foundations of MAUT involve utility functions and weights. Other methods, such as the *Analytic Hierarchy Process* [AHP] and the *Best-Worst Method* [BWM], provide structured frameworks for prioritizing options. AHP uses pairwise comparisons and normalized principal eigenvectors, while BWM simplifies the process by focusing on the best and worst criteria. Simplified methods like summary charts and multi-criteria checklists offer accessible alternatives for decision-makers lacking resources or expertise in complex MCA techniques.

MCA can be implemented using non-participatory or participatory approaches. Non-participatory approaches involve independent analysis, while participatory approaches incorporate stakeholder input, adding complexity but enhancing inclusivity and informed decision-making. The choice of method depends on factors such as the decision problem's complexity, available resources, and stakeholder engagement.

Trade-off weighting techniques determine criteria weights through comparisons and adjustments based on changes in performance scores. The Swing Weighting Technique simplifies this process by ranking hypothetical options to derive weights. Non-compensatory weighting techniques, such as Simple Rating and Point Allocation, assign weights based on criteria importance without trade-offs.

Overall, MCA emphasizes the importance of transparency and the need for careful consideration of various techniques to achieve a comprehensive and reliable assessment in bridge management. By adopting MCA, BM can integrate multiple criteria, enhancing the decision-making process and ensuring the optimal allocation of resources and interventions for bridge maintenance and resilience.

Research aimed to bring rationale to the decision-making processes by including all known criterion. The approach adopted is Formal Discrete aggregation methodology. MCA brings in distinct advantages in decision-making. Consistent and logical soundness coupled with transparency, and ease of usage, which enables changes and accountability to decision-making process. It permits the decision-making hierarchy to implement judgement within the process. MCA being a structured analysis process does not differentiates welfare or sufferings that an action brings about.

2: PROBLEM STATEMENT

Current bridge designs rely on static models that assume natural hazards will occur with predictable frequency and severity. However, dynamism has disrupted these assumptions. The increasing dynamism of natural hazards has led to natural hazard occurrence of greater intensity and frequency. Such events are far more destructive. This demands an urgent attention and solution.

The existing designs do not cater to the need of resilience, which is crucial to withstand the accelerating impacts of these hazards. In response to rapid urbanization and growing infrastructure demands, India has undertaken large-scale bridge and infrastructure construction projects over the past few decades. However, economic constraints and the need to expedite construction have led to the adoption of cost-effective practices, such as the "Design and Build". While this method allows for quicker project delivery, it often favors economical designs, which may not fully address the long-term resilience. The lack of stringent resilience requirements has left many of India’s bridges vulnerable to rapid deterioration and high potential of failure in the face of unexpected natural forces.

Application of Multi-Criteria Decision-Making [MCDM] to enhance resilience in bridges requires specific adjustments that will ensure to give due weightage to risk assessment of the bridge. Assignment of weightage needs to succeed the process of assigning priority rank. Based on the user organization policy, these ranking of criteria happens. Risk assessment if accorded highest rank, it ensures higher weightage to this criteria leading to enhancement of Resilience.

3: OBJECTIVES

The research objectives aims to address the knowledge gap in current bridge design practices and strategies for enhancing resilience to natural hazards. Absence of MCDM in the classical Bridge Management System results in elimination of all other criteria that need considerations[3]. The objectives include:

a. **Comprehensive Risk Assessment:**
   Conduct an in-depth risk analysis across India. Division of India into various regions to identify the natural hazard [floods, earthquakes, landslides, and cyclones] vulnerability.

b. **Evaluating Impact:**
   Analyse the structural vulnerabilities of bridges when exposed to these hazards, focusing on key parameters such as span geometry, foundations, and material composition.

c. **Identifying Design Gaps:**
   Identify the deficiencies that arise with respect to the unpredictable forces induced by climate change and recommending changes to enhance resilience within the bridge structure.

d. **Define Resilience Boundaries:**
   Define the geometrical boundaries for various components of a resilient bridge. Identify the probability of survival of the entire bridge structure of given dimension in given location.

e. **Providing Regional Insights:**
   Offering region-specific recommendations, as different parts of India face unique combinations of hazards.

f. **Integration of MCDM within BMS:**
   Define criteria that needs consideration within BMS decision-making process and provide functionality to assign importance to criterion's as per the organization policy.

Strengthen the design approach to usher resilience in bridges, integrating climate-resilience principles are the overarching goal of this research. Result yields methods that can increment the probability of survival in bridges, ensuring that they remain functional and safe despite the evolving challenges posed by climate change. Fund optimization, the goal and focus of BMS, gets more realistic by integration of MCDM. Research serves as a knowledge base for policymakers and engineers, guiding the development of future designs, incorporating resilience-enhancing measures tailored to the diverse geographical vulnerabilities.

4: LITERATURE REVIEW

A well-founded literature review, essential for understanding the complexities of hazard resilience and risk mitigation in infrastructure, particularly for bridges. Two key studies provide valuable insights into the intersection of climate change, infrastructure vulnerability, and regional disaster risks.

1. Climate Change and Infrastructure Resilience:

According to a report by the Intergovernmental Panel on Climate Change (IPCC), climate change is accelerating the frequency and severity of natural disasters such as floods, cyclones, and landslides. The report highlights that infrastructure in developing nations, including India, is particularly vulnerable due to shortcomings in designs and insufficient adaptation strategies[4]. IPCC emphasizes the need for proactive resilience planning to minimize the long-term socio-economic impacts of climate-induced disasters.

This study underscores that regions with high rainfall variability require tailored flood mitigation measures to safeguard critical infrastructure. Building adaptive bridges capable of withstanding extreme weather events is vital to ensure continuity in transportation and logistics during emergencies.

Image Credit 02: TWC India Edit Team (Himachal, Uttarakhand Bridges)

2. Seismic Risk and Infrastructure Vulnerability

A pivotal study by Bilham et al. (2001) on seismic risks in India explores the vulnerability of bridges and public infrastructure in seismic-prone regions[5]. Bilham reveals that the Indian subcontinent lies atop active fault lines, with areas like the North region, Himalayan belt, and parts of Gujarat falling within high-risk seismic zones.

Bilham's findings are particularly relevant for infrastructure planning in Seismic Zones IV and V, where even moderate seismic events can result in severe structural damage. Proactive investments are essential to render structures resilient to reduce the probability of catastrophic infrastructure failures.

Above two studies, along with other research paper emphasize the importance of integrating climate adaptation and seismic resilience into infrastructure planning. The findings highlight that addressing regional hazards like floods, cyclones, and earthquakes requires proactive risk assessments and investment in adaptive infrastructure.

5: METHODOLOGY

Research utilizes systematic approach that integrates data collection and analysis using advanced tools and techniques. Data collection's primary goal ensure to collect and collate relevant data, assess vulnerability, and apply appropriate resilience-enhancing strategies for bridge infrastructure globally by keeping the focus on bridges in India.

Data Collection:

Effective data collection is a crucial component of this research, as it enables the identification of vulnerabilities and informs the development of resilience strategies[6]. The data collection process structured around two main components: Hazard-specific data and Bridge infrastructure data.

1. **Hazard-Specific Data:** Collects data on four primary natural hazards—floods, cyclones, landslides, and earthquakes—affecting different regions of India. This includes:

- **Historical Narrative:** Data on the frequency, intensity, and severity of past natural hazard events.
- **Climate Change Projections:** Future hazard scenarios based on climate change models, which predict shifts in the frequency and intensity of events like cyclones, floods, and seismic activity.
- **Geographical Data:** Topographical and geographical characteristics of different regions, such as river basin maps, fault lines, soil composition, and elevation, which influence the impact of natural hazards on bridges.

2. **Bridge Infrastructure Data:** Data on existing bridges collected, assess the current structural status to define the resilience levels[7,8]. This includes:

- **Structural Data:** Information on bridge geometry (span length, foundation depth, material type), structural condition, age, and maintenance history.
- **Performance Data:** Past performance of bridges during natural disasters, including records of damages, repairs, and collapses.
- **Knowledge Related to Designing:** The gathered information serves as a crucial basis for risk assessment and analysis, enabling the study to pinpoint the most susceptible bridges and regions while also revealing specific areas where design improvements are necessary.

Tools & Techniques:

Research deploy a combination of advanced tools and techniques to analyse the data and formulate resilience-enhancing strategies[9]. These tools and techniques focus on data analysis tools and engineering assessment tools.

1. Data Analysis Tools:

- **Geographical Information Systems (GIS):** GIS tools used to map hazard-prone regions and overlay this information with bridge locations.
- **Statistical Tools:** Analytical tools employed to examine historical hazard data and bridge performance statistics.
- **Risk Modelling:** Simulation models used to assess the impact of natural hazards on bridge structures, providing probabilistic evaluations of damage across various hazard scenarios.

2. Engineering Assessment Tools:

- **Structural Analysis Software:** These tools assess how bridges perform under varying stress conditions such as floods, seismic events, or strong winds.
- **Finite Element Analysis (FEA):** FEA applied to model stress, strain behaviour of bridge materials under various natural hazard conditions.
- **Vulnerability Assessment Models:** Models such as Fragility Curves used to determine the likelihood of bridge failure under specific hazard intensities.

Implementation Process:

Once the data has been collected and analyzed, the implementation of resilience-enhancing strategies proceeds through the following stages:

1. **Risk Categorization:** Categorization of Bridges based on their risk exposure to different natural hazards.

2. **Design Reassessment**: Current design practices evaluated against the updated hazard data.

3. **Resilience Strategy Development**: Based on the vulnerability assessment, tailored resilience-enhancing solutions developed.

4. **Retrofitting Recommendations**: For existing bridges, retrofitting strategies proposed based on the identified vulnerabilities. By integrating geographic, structural, and hazard-specific data, the study provides a comprehensive framework for assessing bridge resilience across India.

6: DATA ANALYSIS: HAZARD ASSESSMENT BY REGION

We assess the natural hazard risks across four major regions in India—North, Eastern, West Central, and Southern regions. Each region experiences distinct types and intensities of natural hazards due to geographical and environmental factors.

The states of India categorized into four distinct regions, each primarily exposed to for major hazards: Flooding, Cyclones, Landslides, and Earthquakes.

1. North Region
2. Eastern Region
3. West Central Region
4. Southern Region

	1	2	3	4
Region	North Region	Eastern Region	West Central Region	Southern Region
Risk	High to Very High Risk	Moderate to High Risk	Moderate Risk	Low to Moderate Risk
Seismic Zone	IV and V	III and IV	II and III	II and III
30 States of India	Jammu & Kashmir	Bihar	Gujarat	Tamil Nadu
	Himachal Pradesh	Jharkhand	Maharashtra	Kerala
	Uttarakhand	West Bengal	Madhya Pradesh	Karnataka
	Punjab	Sikkim		Andhra Pradesh
	Haryana	Assam		
	Delhi	Arunachal Pradesh		Telangana
	Uttar Pradesh	Meghalaya	Chhattisgarh	
		Nagaland		Odisha
	Rajasthan	Manipur	Goa	
		Mizoram		

Table 1: India categorized into four distinct regions

1. North Region:

The North region of India is one of the most hazard-prone areas in the country, characterized by a high susceptibility to natural hazards such as earthquakes, floods, cyclones, and landslides. The region lies predominantly within Seismic Zones IV and V, which highlights the high likelihood of severe earthquakes.

Flooding:

Due to intense monsoon rains, the region frequently experiences flooding. These floods can last several days, resulting in substantial infrastructure damage, particularly to bridges.

Cyclones:

Although cyclones are less frequent compared to floods, they still pose a serious threat to coastal and low-lying areas.

Landslides:

The region's hilly terrain makes it highly vulnerable to landslides, which are especially common during the rainy season.

Earthquakes:

The North region known for its frequent seismic activity, with earthquakes being a common occurrence. These events can cause severe structural damage to buildings and infrastructure, including bridges, making them a significant risk factor.

The suggested ratings for natural hazards for this region can be as follows:

Hazard	NORTH
Rating for Floodi	4
Rating for Cyclon	2
Rating for Landsli	3
Rating for Earthquake	4

Table 2: Ratings recommended for North region

2. Eastern Region

The Eastern region of India, face moderate to high risks from flooding, cyclones, landslides, and occasional earthquakes. The region lies mostly in Seismic Zones III and IV, meaning it is less prone to earthquakes compared to the North region, but still at risk.

Flooding:

Flooding is a recurrent hazard in the Eastern region, particularly during the monsoon season. Ganges and Brahmaputra swell during heavy rains, causing long-lasting floods that severely damage infrastructure, especially bridges along riverbanks.

Cyclones:

The Bay of Bengal serves as a major cyclone development zone. Cyclones in this region are frequent and often severe, leading to widespread destruction, especially along the coasts.

Landslides:

Although less frequent than in the North East, landslides occur mainly in the hill ranges of West Bengal and Sikkim.

Earthquakes:

The risk of earthquakes in the Eastern region is moderate, but it still exists, especially in northern Bihar and parts of West Bengal.

The suggested ratings for natural hazards for this region can be as follows:

Hazard	EASTERN
Rating for Floodi	3
Rating for Cyclon	3
Rating for Landslide	3
Rating Earthqua	3

Table 3: Ratings recommended for Eastern region

3. West Central Region

The West Central region, encompassing states like Maharashtra, Madhya Pradesh, and Gujarat, faces moderate risks from natural hazards. Flooding is the most frequent concern, and the region lies in Seismic Zones II and III, indicating moderate earthquake vulnerability.

Flooding:

This region experiences seasonal monsoon flooding, especially along riverbanks, which can last for weeks and cause significant infrastructure damage, particularly to bridges.

Cyclones:

While cyclones are less frequent compared to coastal areas, occasional events still result in localized damage.

Landslides:

Though rare, landslides can occur in hilly areas, notably in Maharashtra, disrupting transportation and infrastructure.

Earthquakes:

The region is prone to moderate seismic activity, with Gujarat being a hotspot for occasional significant earthquakes, posing risks to buildings and bridges.

The suggested ratings for natural hazards for this region can be as follows:

Hazard	WEST CENTRAL
Rating for Floodi	3
Rating for Cyclon	2
Rating for Landslide	3
Rating Earthqua	2

Table 4: Ratings recommended for West Central region

4. Southern Region

The Southern region, which includes states like Tamil Nadu, Kerala, Karnataka, and Andhra Pradesh, faces relatively lower natural disaster risks compared to other parts of India. However, flooding and cyclones still pose occasional challenges. Most of the region lies in Seismic Zones II and III, indicating a lower earthquake threat.

Flooding:

Heavy monsoon rains, particularly in Kerala and Tamil Nadu, often cause flooding, disrupting transportation and damaging bridges and roads.

Cyclones:

While cyclones are less frequent in the South, those that develop along the coasts can cause severe damage, especially in Tamil Nadu and Andhra Pradesh.

Landslides:

Hilly regions, especially along the West Ghats, are prone to landslides during the monsoon, affecting rural infrastructure and roadways.

Earthquakes:

The region experiences minimal seismic activity, though isolated events recorded without causing widespread damage.

The suggested ratings for natural hazards for this region can be as follows:

Hazard	**SOUTHERN**
Rating for Floodin	3
Rating for Cyclone	3
Rating for Landsli	2
Rating for Earthqua	2

Table 5: Ratings recommended for Southern region

7: INTEGRATION OF MCDM:

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[10]. 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[11,12].

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[13].

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

1. Mechanical process
2. Physical process
3. 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 durations (36 – 48 hours) and then repeated three to four times, at intervals of three to four months, reveal the decrement in performance[14]. 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[15,16]. 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 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[17]. 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[18]. 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:

a) Distress in bridge
b) Economic growth potential of the bridge
c) Socio-economic importance of the bridge
d) 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[21]. 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

Table 6: Assignment of score for each criterion as per value function scale

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

Structural status / Level tress

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

Economic growth potential

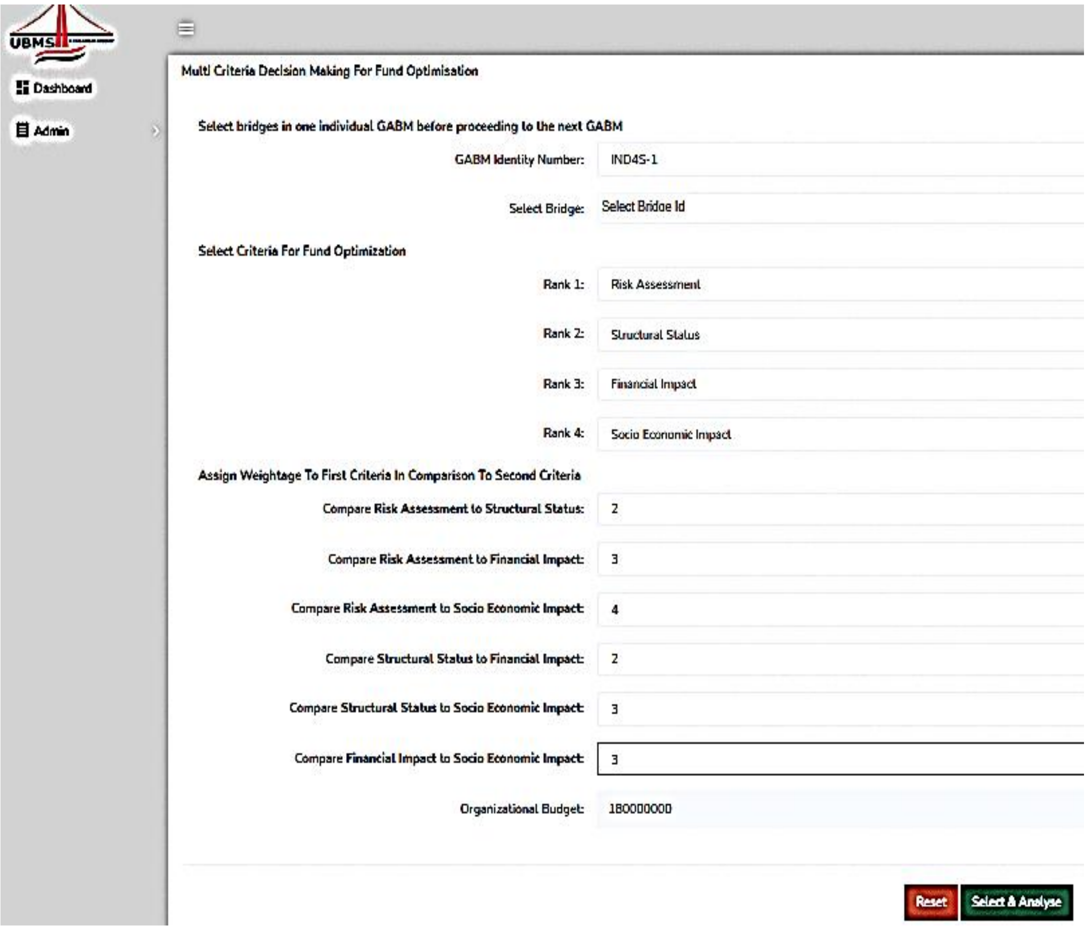
Scale value	Description
1	Tangible IRR divided by Nontangible IRR less than 1.25
2	Tangible IRR divided by Non-tangible IRR greater than 1.25 but less than 1.5
3	Tangible IRR divided by Non-tangible IRR greater than 1.5 but less than 1.75
4	Tangible IRR divided by Non-tangible IRR greater than 1.75 but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

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

Table 7: 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.



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

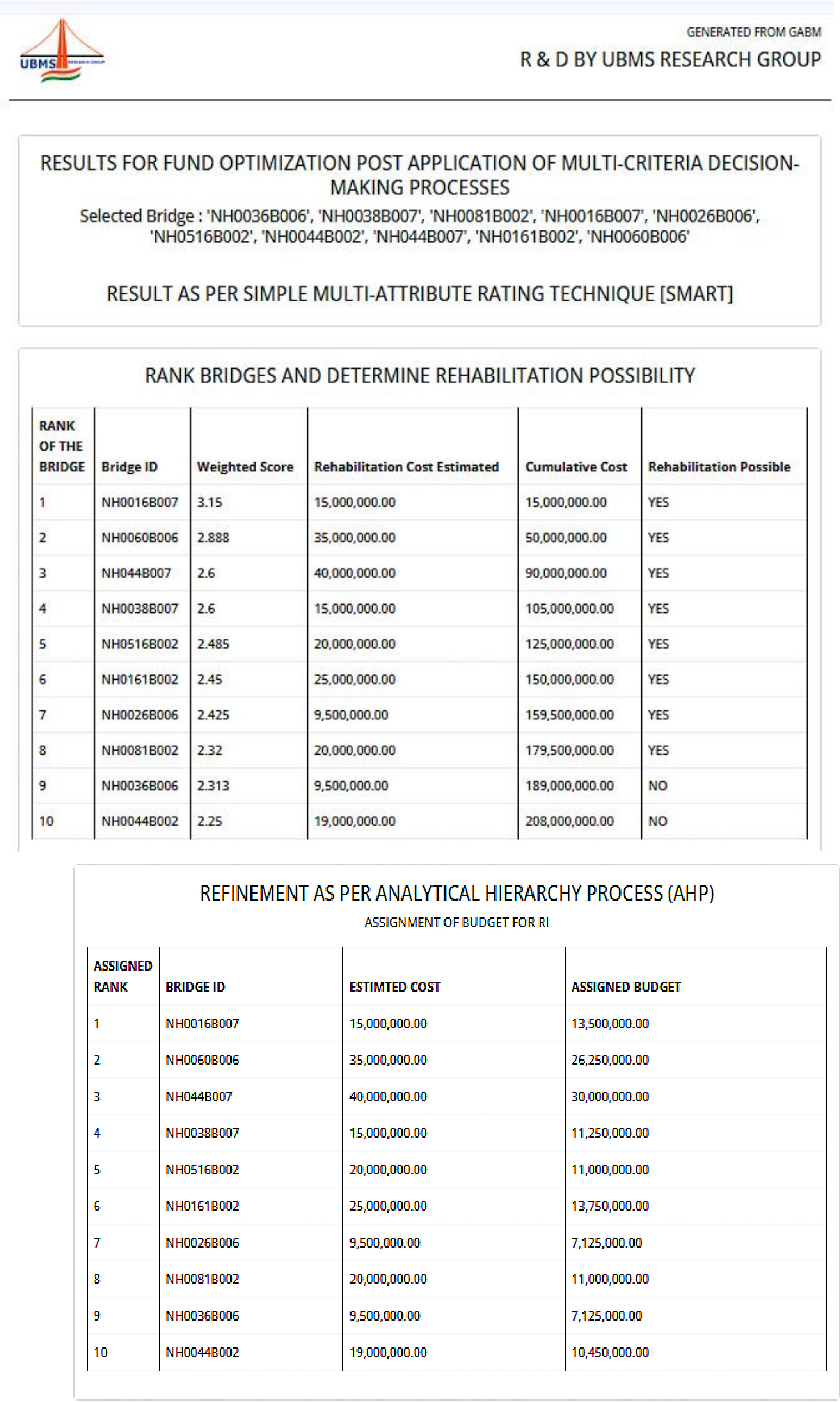
Compare Structural Status to Financial Impact: 2

Compare Structural Status to Socio Economic Impact: 3

Compare Financial Impact to Socio Economic Impact: 3

Organizational Budget: 180000000

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[22]. 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.



GENERATED FROM GABM

R & D BY UBMS RESEARCH GROUP

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]

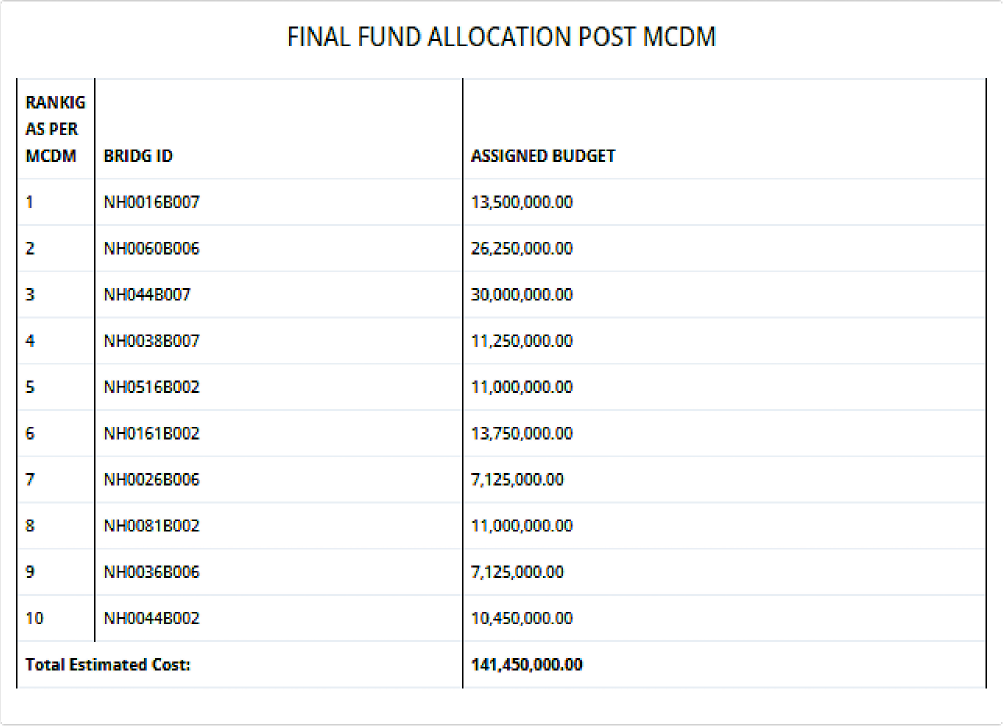
RANK BRIDGES AND DETERMINE REHABILITATION POSSIBILITY

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



FINAL FUND ALLOCATION POST MCDM

RANKIG AS PER MCDM	BRIDG ID	ASSIGNED BUDGET
1	NH0016B007	13,500,000.00
2	NH0060B006	26,250,000.00
3	NH044B007	30,000,000.00
4	NH0038B007	11,250,000.00
5	NH0516B002	11,000,000.00
6	NH0161B002	13,750,000.00
7	NH0026B006	7,125,000.00
8	NH0081B002	11,000,000.00
9	NH0036B006	7,125,000.00
10	NH0044B002	10,450,000.00
Total Estimated Cost:		**141,450,000.00**

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[23]. A reduction of estimated budget introduced to ensure all bridges get funds in their ranked priority manner so that every bridge attended.

8: Analytical Results using GABM and GARM

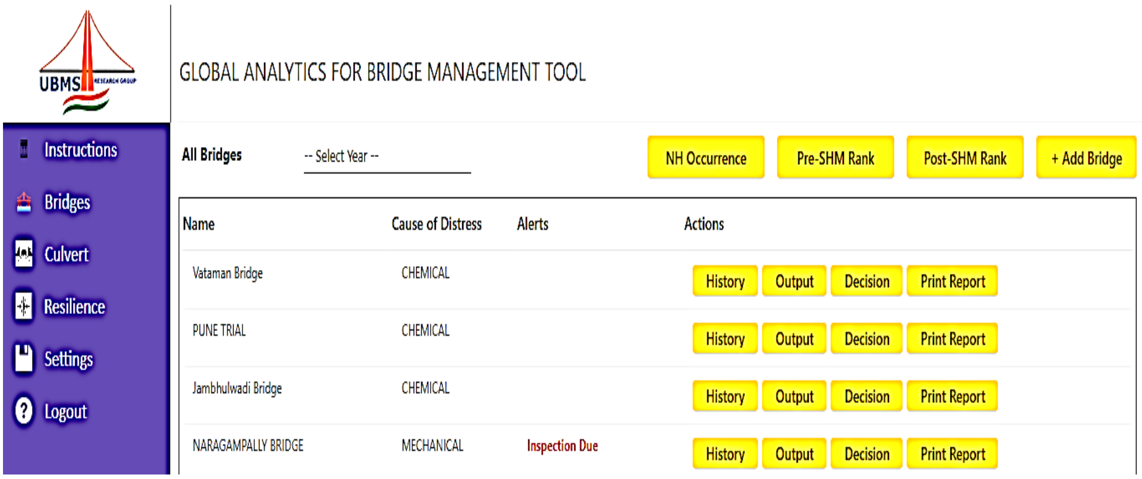
Bridge management is a complex, ever-evolving field, where the integration of global analytics plays a crucial role in ensuring the longevity and safety of infrastructure. As bridges continue to face challenges from aging, environmental factors, and increasing traffic demands, advanced data-driven solutions are essential for informed decision-making.

Global Analytics for Bridge Management [GABM] and Global Analytics for Resilience and Risk Management [GARM] researched and evolved by UBMS Research Group [URG]. The duo of GABM and GARM applications are very innovative and probably the only Bridge Management system, which provide valuable details into:

1. GABM integrates Symptoms, Cause of Distress and Short term Structural health monitoring. This enables evaluation Balance and Absolute service life [BSL and ABSL] irrespective of the age of the bridge.
2. GABM enables evaluation of vulnerability and risk index for the bridge by combining the geographical risk index with the geometry and structural health of the bridge.
3. GABM ensures proper financial due diligence within BMS. It provides life cycle management for the entire life of the bridge.
4. GARM has Multi-Criteria Decision-Making process enabling Decision-Making by considering structural health of the bridge, along with risk assessment, financial due diligence and the socio-economic impact of the bridge.
5. GARM provides feasibility of providing funds to individual bridge and collectively for all bridges for rehabilitation strengthening and enhancement of resilience effectively.

By harnessing the power of GABM and GARM, we can enhance resilience, reduce risks, and optimize budget allocations. Through continuous monitoring, smart technologies, and comprehensive assessments, we can safeguard vital transportation links, ensuring their operational efficiency, sustainability, and safety for years to come.

ANALYTICAL RESULTS: Outputs and reports generated by GABM by using **PRINT REPORT** button.



Name	Cause of Distress	Alerts	Actions
Vataman Bridge	CHEMICAL		History Output Decision Print Report
PUNE TRIAL	CHEMICAL		History Output Decision Print Report
Jambhulwadi Bridge	CHEMICAL		History Output Decision Print Report
NARAGAMPALLY BRIDGE	MECHANICAL	Inspection Due	History Output Decision Print Report

GLOBAL ANALYTICS FOR BRIDGE MANAGEMENT TOOL 0478534118

Vataman Bridge-Bridge History

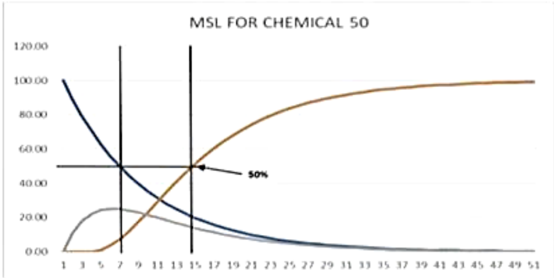
Description	1st Year	2nd Year	3rd Year	4th Year
YEAR OF INPUT	2021	2022	2023	2024
DEPARTMENTAL BUDGET FOR PARTICULAR YEAR	100000.0	10000.0	100000.0	100000.0
ESTIMATE FOR REHABILITATION FOR EACH BRIDGE	12500000.0	17500000.0	25000000.0	35000000.0
BRIDGE IDENTITY				
GABM Id	AUS1-1	AUS1-1	AUS1-1	AUS1-1
Length in meters	300	300	300	300
Total No. of Spans	6	6	6	6
Span Length	50	50	50	50
Latitude	22.4928	22.4928	22.4928	22.4928
Longitude	72.4269	72.4269	72.4269	72.4269
CLASSIFICATION				
Traffic Lane	4	4	4	4
Type of Road	1	1	1	1
Age of Bridge	30	31	32	33
Load Capacity	70000	70000	70000	70000
Foundation Type	Pile foundation	Pile foundation	Pile foundation	Pile foundation
BRIDGE STRUCTURAL RATING NUMBER [BSRN]				
Deck Rating	2	3	3	3
Superstructure	3	3	4	4
Substructure	2	3	3	3
Foundation	2	3	3	3
BRIDGE FUNCTIONAL RATING NUMBER [BFRN]				
Deck Geometry	2	2	2	2
Vertical Clearance	2	2	2	2
Waterway	3	3	3	3
ADT	3	3	3	3
SOCIO-ECONOMIC RATING NUMBER [SERN]				
Social Importance	2	2	2	2
Economic Growth	3	3	3	3
Alternate Route	2	2	2	2
Enviorno Impact	3	3	3	3
CAUSE MATRIX				
Impact (M1)	2	2	2	2
Abrasion (M2)	2	2	2	2
Erosion (M3)	2	1	1	2
Overload (M4)	2	2	3	3
Fatique (M5)	2	2	3	3
Temperature (P1)	2	2	2	2
Shrinkage (P2)	2	2	2	2
Settlement (P3)	2	2	2	2
Chloride Attack (C1)	3	3	4	4
Sulphates (C2)	2	2	2	2
Carbonation (C3)	3	3	4	4
Alkali-Aggregate (C4)	2	2	2	2
Total of Cause Ratings	24	23	27	28
DATA FROM SHORT TERM STURUCTURAL HEALTH MONITORING				
SHM Change Rating				
Construction Cost Per KM	12666.667	12666.667	12666.667	12666.667

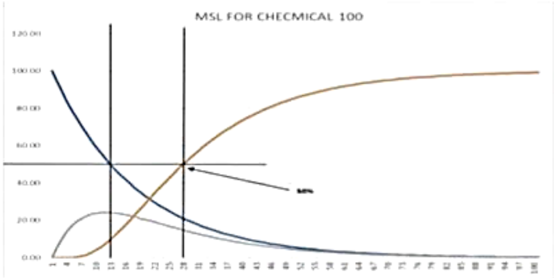
Description	1st Year	2nd Year	3rd Year	4th Year
Years Over Which Investment Is Spread	5	5	5	5
Conversion Ratio of Financial to Economic	0.85	0.85	0.85	0.85

Output - Vataman Bridge
-Bridge is in severe distress

Description	1st Year	2nd Year	3rd Year	4th Year
YEAR OF INPUT	2021	2022	2023	2024
DEPARTMENTAL BUDGET FOR PARTICULAR YEAR	100000.0	10000.0	100000.0	100000.0
ESTIMATE FOR REHABILITATION FOR EACH BRIDGE	12500000.0	17500000.0	25000000.0	35000000.0
RANKING AND PRIORITY				
50 Years Design Life				
Deterioration time in Years (DT/ BSL)	4.56	4.60	4.68	4.63
Median Service Life in Years (MSL)	13.77	13.77	13.77	13.77
Absolute Balance Service Life in years	2.19	2.21	2.29	2.22
100 Years Design Life				
Deterioration time in Years (DT/ BSL)	7.97	8.03	8.16	8.10
Median Service Life in Years (MSL)	26.92	26.92	26.92	26.92
Absolute Balance Service Life in years	4.54	4.50	4.57	4.46
Engineering Impact Index	3.4%	3.4%	3.4%	3.4%
Financial Impact Index	11.24%	11.49%	11.44%	11.38%
Sustainability Index	3.10%	3.07%	3.07%	2.66%
Risk Index	0.82%	0.94%	1.09%	1.12%
Final Cost	4.6400%	4.7250%	4.7500%	4.6400%
Wsum	150	100	100	100
Life Cycle Cost Analysis (LCCA)				
STANDARD IRR	9.91	9.91	9.72	9.56
ENHANCED IRR	25.99	27.05	26.91	26.70
CAUSE OF DISTRESS	CHEMICAL	CHEMICAL	CHEMICAL	CHEMICAL
CURRENT STATUS OF BRIDGE	Bridge is Safe	Bridge is Safe	-Bridge is in severe distress	-Bridge is in severe distress

Bridge Output -



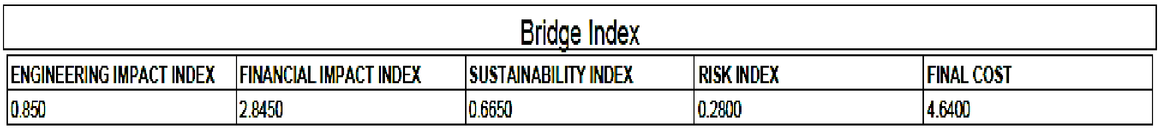


SERVICE LIFE EVALUATED - PRE SHM

DESIGNED SERVICE LIFE	BALANCE SERVICE LIFE	ABSOLUTE BALANCE SERVICE LIFE	MEDIAN SERVICE LIFE
50 Years	4.63	2.22	13.77
100 Years	8.10	4.46	26.92

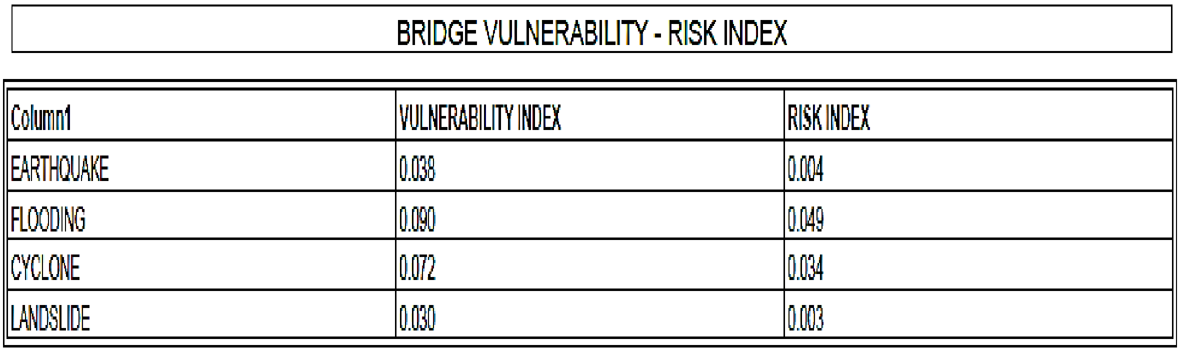
100 YEARS LIFE CYCLE COST ANALYSIS RESULTS

IRR(ONLY DIRECT IMPACT)	IRR(INCLUSIVE OF INDIRECT)
9.56	26.70



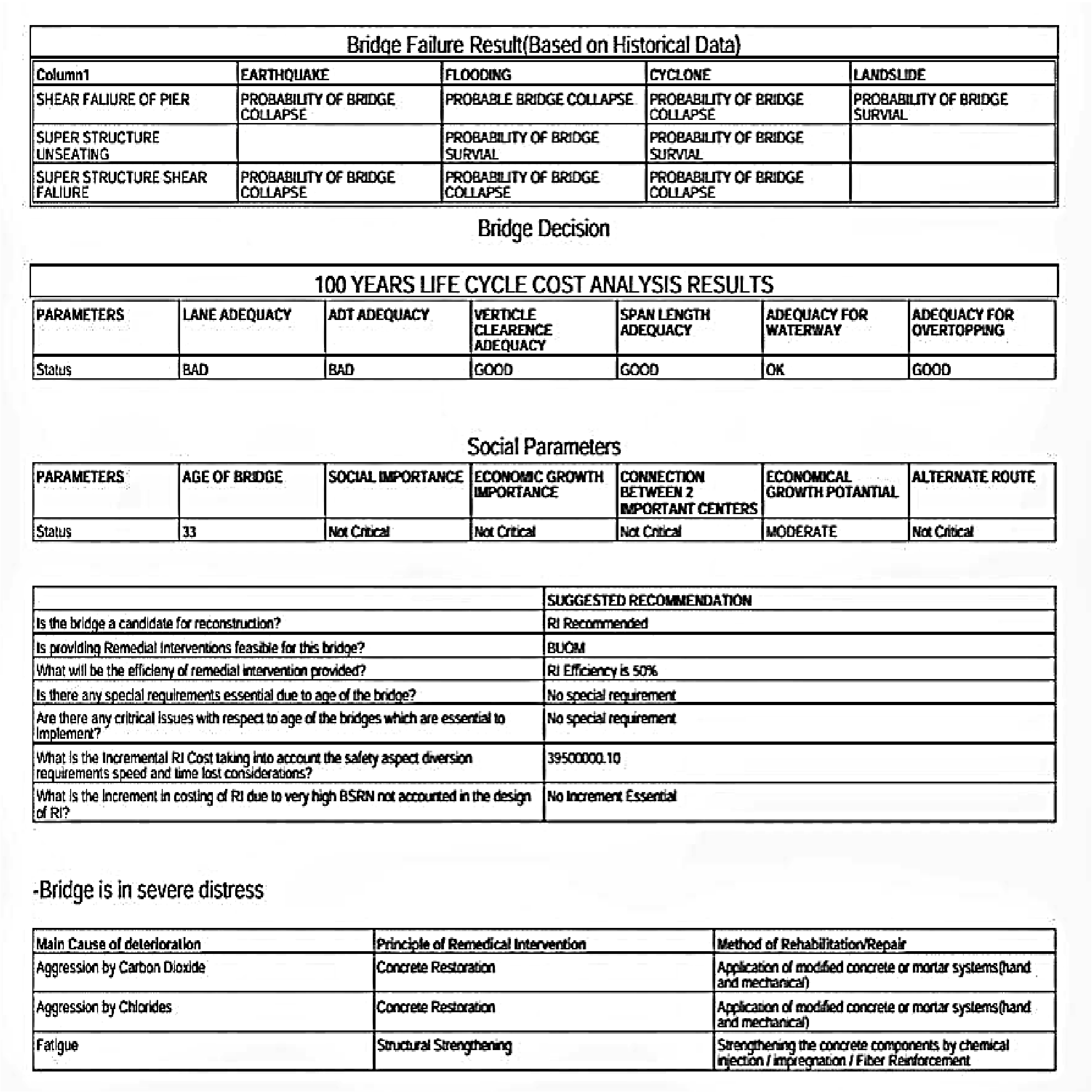
Bridge Index

ENGINEERING IMPACT INDEX	FINANCIAL IMPACT INDEX	SUSTAINABILITY INDEX	RISK INDEX	FINAL COST
0.850	2.8450	0.6650	0.2800	4.6400



BRIDGE VULNERABILITY - RISK INDEX

Column1	VULNERABILITY INDEX	RISK INDEX
EARTHQUAKE	0.038	0.004
FLOODING	0.090	0.049
CYCLONE	0.072	0.034
LANDSLIDE	0.030	0.003



Bridge Failure Result(Based on Historical Data)

Column1	EARTHQUAKE	FLOODING	CYCLONE	LANDSLIDE
SHEAR FALIURE OF PIER	PROBABILITY OF BRIDGE COLLAPSE	PROBABLE BRIDGE COLLAPSE	PROBABILITY OF BRIDGE COLLAPSE	PROBABILITY OF BRIDGE SURVIAL
SUPER STRUCTURE UNSEATING		PROBABILITY OF BRIDGE SURVIAL	PROBABILITY OF BRIDGE SURVIAL	
SUPER STRUCTURE SHEAR FALIURE	PROBABILITY OF BRIDGE COLLAPSE	PROBABILITY OF BRIDGE COLLAPSE	PROBABILITY OF BRIDGE COLLAPSE	

Bridge Decision

100 YEARS LIFE CYCLE COST ANALYSIS RESULTS

PARAMETERS	LANE ADEQUACY	ADT ADEQUACY	VERTICLE CLEARENCE ADEQUACY	SPAN LENGTH ADEQUACY	ADEQUACY FOR WATERWAY	ADEQUACY FOR OVERTOPPING
Status	BAD	BAD	GOOD	GOOD	OK	GOOD

Social Parameters

PARAMETERS	AGE OF BRIDGE	SOCIAL IMPORTANCE	ECONOMIC GROWTH IMPORTANCE	CONNECTION BETWEEN 2 IMPORTANT CENTERS	ECONOMICAL GROWTH POTANTIAL	ALTERNATE ROUTE
Status	33	Not Critical	Not Critical	Not Critical	MODERATE	Not Critical

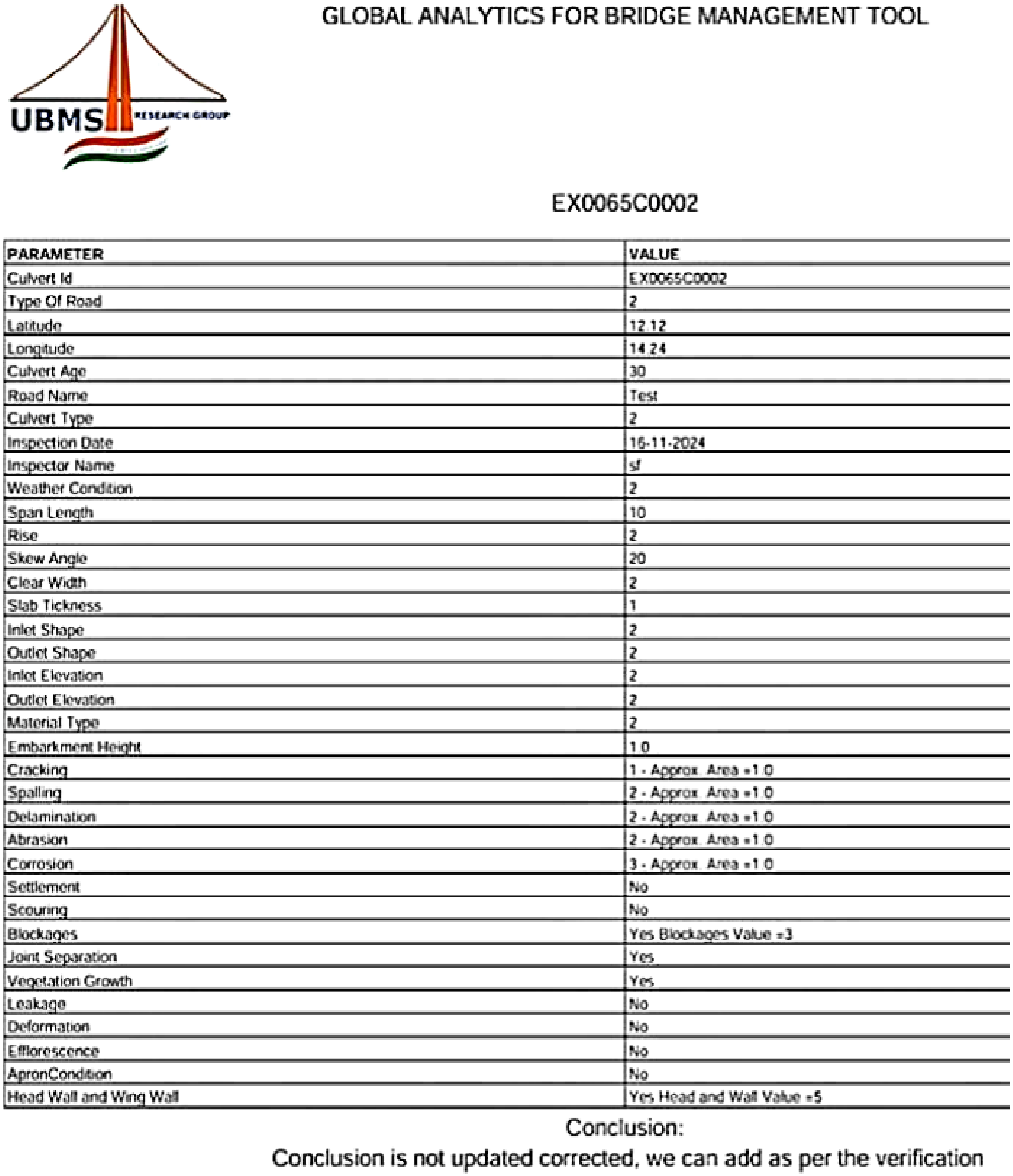
	SUGGESTED RECOMMENDATION
Is the bridge a candidate for reconstruction?	RI Recommended
Is providing Remedial Interventions feasible for this bridge?	BUOM
What will be the efficieny of remedial intervention provided?	RI Efficiency is 50%
Is there any special requirements essential due to age of the bridge?	No special requirement
Are there any critrical issues with respect to age of the bridges which are essential to implement?	No special requirement
What is the Incremental RI Cost taking into account the safety aspect diversion requirements speed and time lost considerations?	39500000.10
What is the increment in costing of RI due to very high BSRN not accounted in the design of RI?	No Increment Essential

-Bridge is in severe distress

Main Cause of deterioration	Principle of Remedical Intervention	Method of Rehabilitation/Repair
Aggression by Carbon Dioxide	Concrete Restoration	Application of modified concrete or mortar systems(hand and mechanical)
Aggression by Chlorides	Concrete Restoration	Application of modified concrete or mortar systems(hand and mechanical)
Fatigue	Structural Strengthening	Strengthening the concrete components by chemical injection / impregnation / Fiber Reinforcement

GABM provides results for Culverts within the region, where bridge inspections carried out.

Culverts inspection does not involve any analysis and report generated are based on Culvert inspection carried out by the Bridge inspection engineer. The accuracy of area shown in the report depends on the extent of accuracy employed by the engineer during inspection.



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GLOBAL ANALYTICS FOR BRIDGE MANAGEMENT TOOL

EX0065C0002

PARAMETER	VALUE
Culvert Id	EX0065C0002
Type Of Road	2
Latitude	12.12
Longitude	14.24
Culvert Age	30
Road Name	Test
Culvert Type	2
Inspection Date	16-11-2024
Inspector Name	sf
Weather Condition	2
Span Length	10
Rise	2
Skew Angle	20
Clear Width	2
Slab Tickness	1
Inlet Shape	2
Outlet Shape	2
Inlet Elevation	2
Outlet Elevation	2
Material Type	2
Embarkment Height	1.0
Cracking	1 - Approx. Area =1.0
Spalling	2 - Approx. Area =1.0
Delamination	2 - Approx. Area =1.0
Abrasion	2 - Approx. Area =1.0
Corrosion	3 - Approx. Area =1.0
Settlement	No
Scouring	No
Blockages	Yes Blockages Value =3
Joint Separation	Yes
Vegetation Growth	Yes
Leakage	No
Deformation	No
Efflorescence	No
ApronCondition	No
Head Wall and Wing Wall	Yes Head and Wall Value =5

Conclusion:

Conclusion is not updated corrected, we can add as per the verification

INSIGHT INTO RESULTS:

Overview of the Bridge and Key Parameters

➢ Bridge Overview and structural status:

The Bridge under review represents a typical bridge structure. The geometrical parameters assigned are typical. The bridge spans 300 meters with six 50-meter spans, supported by a pile foundations. Age assumed 33 years, and the location near the coast. It serves a critical role in regional transportation by connecting key economic hubs. Designed for high traffic, it accommodates four lanes and is a typical 70R [As per IRC load ratings] capacity bridge. Geospatial details ensures accuracy of location and enables detailed evaluation of geographical impact.

The bridge is located near the coast, thereby has prolonged exposure to environmental impact causing very high probability to corrosion and carbonation. Age related exposure to mechanical stresses, as overloading and fatigue are visible in the bridge structure. Historical narrative in the form of four inspection data available in the report. Historical narrative provides valuable insight into the progression of deterioration and reduction of Balance service life. Bridge Structural Ratings identify the location of increasing deterioration. In the report, observed that ratings for three of the four components are increasing with ratings for superstructure increasing to very severe distress levels. The overall increasing ratings indicates distress cause, which is due to location and geometrical parameters of the bridge. Scrutiny of Cause Matrix ratings confirm our judgement. Corrosion and Carbonation ratings observed to be increasing. Since the bridge is aging symptoms of overloading and fatigue are visible. Cause matrix ratings for these two causes confirm the same. Since the bridge is beyond 50 percent of designed service life [50 years], Short-term structural health monitoring deployed also indicates reduction of performance. All three parameters [Symptoms, Cause matrix and ST-SHM] are self-confirming increased deterioration.

Evaluation of BSL and ABSL done in GABM post scrutiny of age of bridge. Age of bridge indicates the predominant factor affecting evaluation of BSL and ABSL. When the bridge is new and the age is less than 20 percent of Design service life, symptoms are critical factor. From 20 percent to 50 percent of designed service life, Cause matrix play a critical role in evaluation. Post this period, ST-SHM observation are essentially required for accurate analysis of BSL and ABSL.

GABM offers additional information regarding Median Service Life [MSL]. MSL definition is critical to understand how efficient rehabilitation intervention will function. If MSL evaluated is below the age of the bridge and the envelope of the two curves intersects prior to the vertical age line, efficiency of intervention will be lower. The report has various definitions relating to Functionality and Socio-Economic Impact of bridge to help decide feasibility of providing rehabilitation intervention. Efficiency of such intervention also provided.

➢ Structural, Functional and Socio-Economic Impact of Bridge:

Over the years, the deck and substructure ratings have shown gradual changes, signaling ongoing deterioration even with targeted repairs. The superstructure experienced minor improvements, but persistent vulnerabilities highlight the necessity for continuous and comprehensive interventions to address long-term structural challenges effectively.

Study of Functional rating and Socio-Economic ratings help decision-making processes. The bridge geometry indicates satisfactory scenario relating to deck geometry and vertical clearance of the bridge. However, the waterway adequacy is not satisfactory and so also increasing Average Daily Traffic count [ADT] is a cause for worry.

Socio-Economic ratings indicate the importance of the bridge in the region and the impact of the bridge on economic stability and growth of the region. Increasing traffic causes higher environmental impact.

➢ Budgetary Allocations vs. Rehabilitation Estimates:

Global Analytics for Bridge Management emphasizes the strategic use of funds and the growing emphasis on rehabilitation efforts. While the departmental budget has remained relatively stable with minor adjustments, rehabilitation estimates have shown a steady rise over the years. This trend reflects a forward-looking approach to addressing the evolving requirements of bridge maintenance and ensuring long-term functionality. The increasing focus on rehabilitation highlights a commitment to sustainable infrastructure management. To achieve optimal outcomes, aligning consistent budget enhancements with data-driven intervention prioritization can help preserve the bridge's integrity and extend its service life.

➢ Causes of Deterioration, Vulnerability, and Risk Indices

1. Causes of Deterioration:

Chemical factors such as chloride attack and carbonation have progressively compromised the concrete matrix, weakening structural integrity. Mechanical stresses from overloading and fatigue, seen by the micro cracking, affecting long-term durability. Environmental factors like temperature fluctuations, erosion, and abrasion have caused gradual wear but remain relatively stable over time.

To address these issues, advanced concrete restoration techniques can mitigate chemical impacts and enhance structural resilience to mechanical stress. Regular application of protective coatings, combined with real-time monitoring of stress and environmental effects, can minimize deterioration and promote long-term durability.

2. Geographical Vulnerability Assessment

The susceptibility to natural hazards and structural risks evaluated through indices to assess flooding, cyclones, earthquakes, and landslides. This comprehensive assessment provides insights into the bridge’s exposure and resilience, underlining the necessity of effective mitigation strategies.

Flooding:

Flooding emerges as the most significant vulnerability, driven by the potential for water ingress and hydrostatic forces. These factors can compromise structural stability and accelerate material degradation.

Cyclones:

Cyclones pose threat due to high wind loads, which could lead to structural displacement and damage to ancillary components, impacting overall functionality.

Earthquakes and Landslides:

The risks associated with earthquakes and landslides are comparatively lower, reflecting the bridge’s robust design against seismic forces and the region's minimal geological instability.

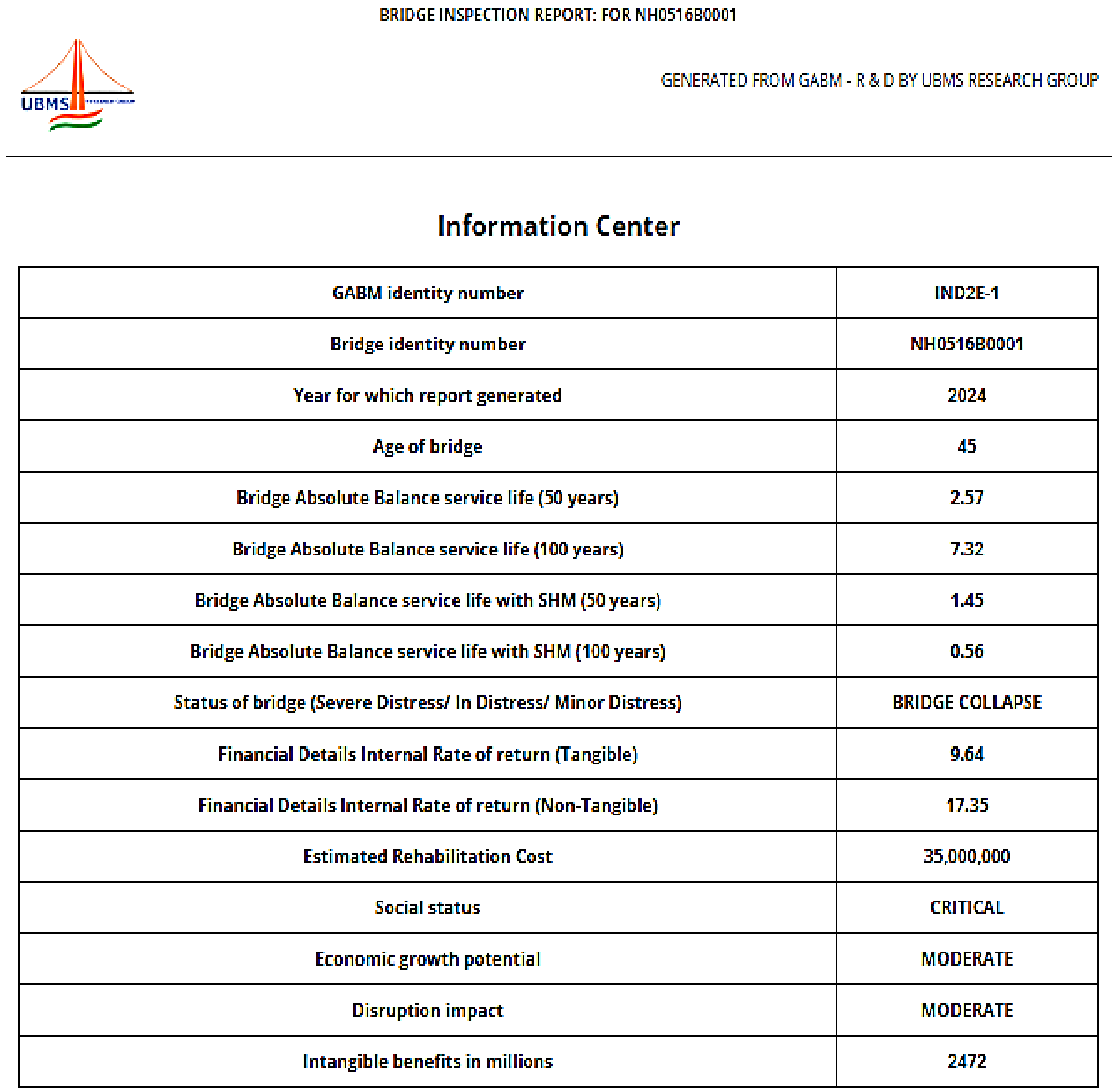
3. Global Analytics for Risk and Resilience Management [GARM]:

Effective risk and resilience management is critical for ensuring the longevity and functionality of infrastructure in bridges. This involves analysing sustainability, financial implications, and overall risk to guide strategic interventions.

The declining sustainability index highlights the increasing challenges in maintaining bridge operations without timely and effective interventions. This underscores the need for proactive measures to enhance operational efficiency and reduce long-term vulnerabilities. A consistently high financial impact index points to significant cost burdens associated with delayed maintenance and rehabilitation. This trend emphasizes the importance of timely investments in repair and upgrade efforts to mitigate escalating financial liabilities. The gradual rise in the risk index signals an increasing probability of partial or complete structural failure. This highlights the urgency of addressing underlying vulnerabilities through comprehensive assessments and targeted resilience strategies.

To enhance the resilience and sustainability of bridge operations, a comprehensive prevention and solution framework is essential. GARM provides such a framework. With Multi-Criteria Decision-Making [MCDM] processes evolved within GARM. Till recently, decisions taken are based on a single criterion of structural status. MCDM applies the criteria of structural health/ status in combination with Risk assessment, Financial due diligence and Socio-Economic impact of the bridge on the region to evaluate the priority of fund allocation for rehabilitation interventions. MCDM uses the dual processes of Simple Multi-Attribute Rating Technique in junction with Analytical Hierarchy Process to evaluate which of the bridges in the set of 10 most critical bridges should funds be provided. Further MCDM also evaluates the financial benefits accrued due to the bridge to the region and compares the same with estimated cost of rehabilitation and resilience enhancement.

GARM integrates data from maximum of six GABM to provide total picture. Each bridge in these six GABM is listed and individual reports and results are available for viewing and printing. Results produced by GARM validate the importance of Risk assessment and MCDM.

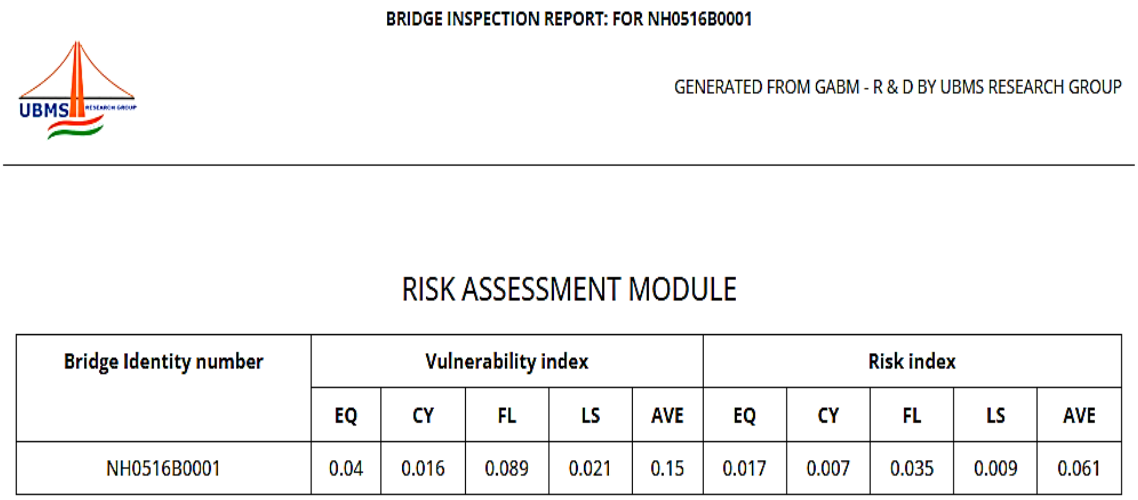


BRIDGE INSPECTION REPORT: FOR NH0516B0001

GENERATED FROM GABM - R & D BY UBMS RESEARCH GROUP

Information Center

GABM identity number	IND2E-1
Bridge identity number	NH0516B0001
Year for which report generated	2024
Age of bridge	45
Bridge Absolute Balance service life (50 years)	2.57
Bridge Absolute Balance service life (100 years)	7.32
Bridge Absolute Balance service life with SHM (50 years)	1.45
Bridge Absolute Balance service life with SHM (100 years)	0.56
Status of bridge (Severe Distress/ In Distress/ Minor Distress)	BRIDGE COLLAPSE
Financial Details Internal Rate of return (Tangible)	9.64
Financial Details Internal Rate of return (Non-Tangible)	17.35
Estimated Rehabilitation Cost	35,000,000
Social status	CRITICAL
Economic growth potential	MODERATE
Disruption impact	MODERATE
Intangible benefits in millions	2472

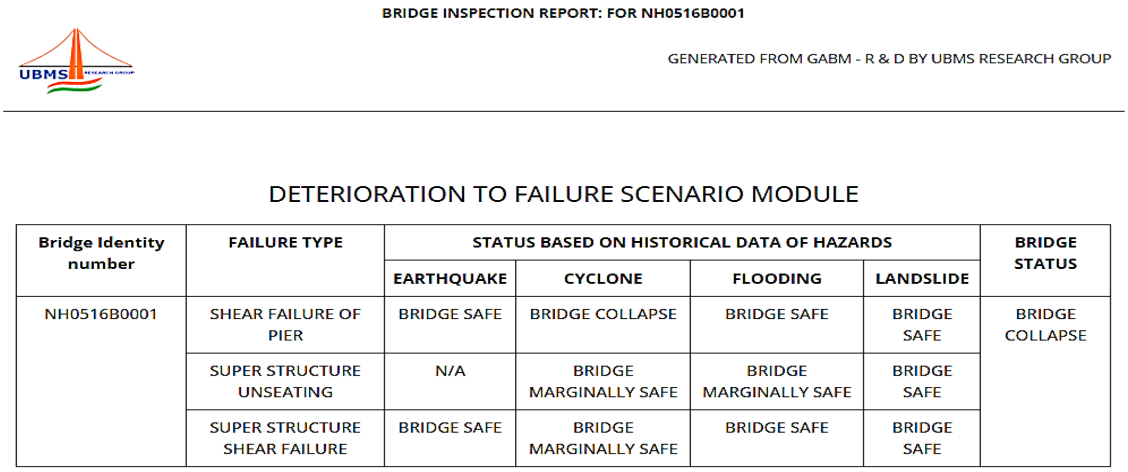


BRIDGE INSPECTION REPORT: FOR NH0516B0001

GENERATED FROM GABM - R & D BY UBMS RESEARCH GROUP

RISK ASSESSMENT MODULE

Bridge Identity number	Vulnerability index					Risk index				
	EQ	CY	FL	LS	AVE	EQ	CY	FL	LS	AVE
NH0516B0001	0.04	0.016	0.089	0.021	0.15	0.017	0.007	0.035	0.009	0.061

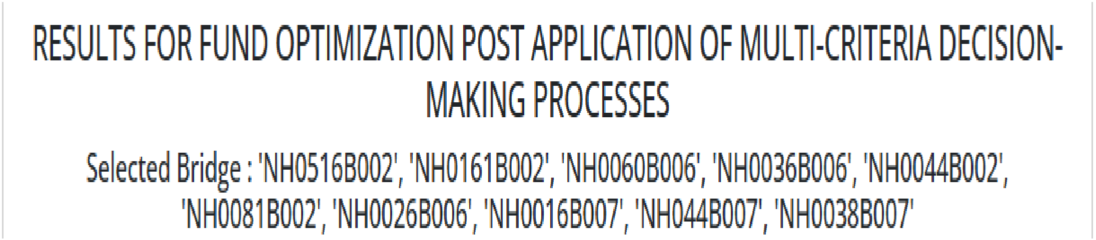


BRIDGE INSPECTION REPORT: FOR NH0516B0001

GENERATED FROM GABM - R & D BY UBMS RESEARCH GROUP

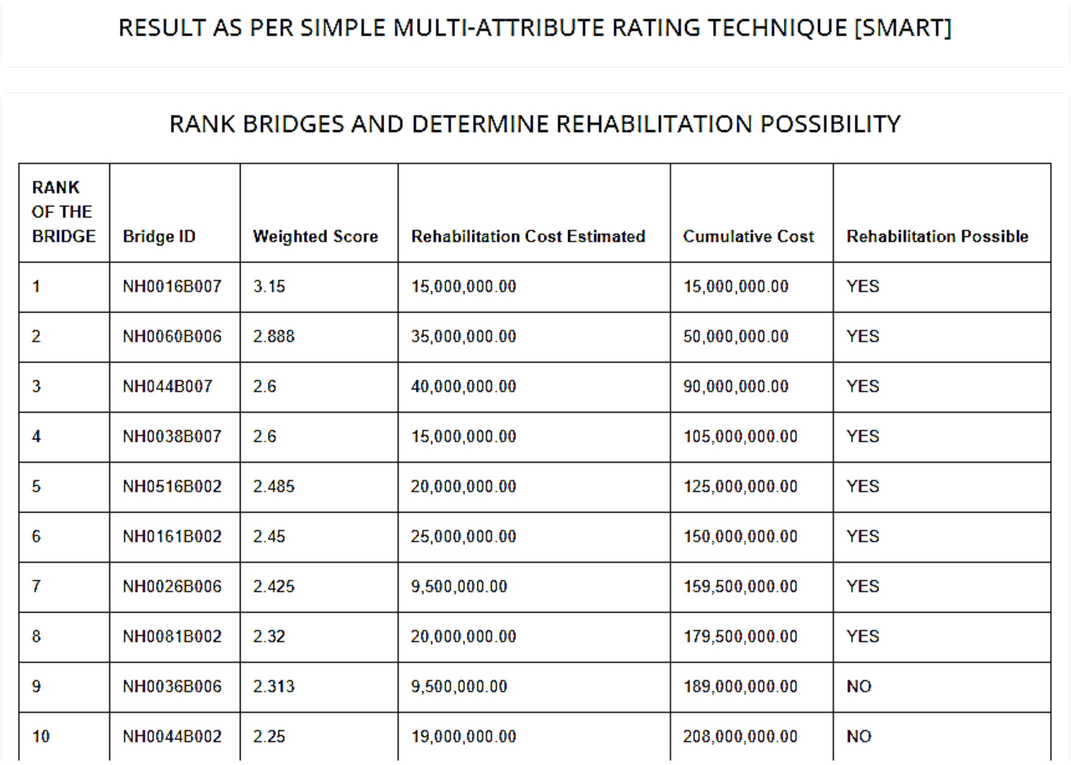
DETERIORATION TO FAILURE SCENARIO MODULE

Bridge Identity number	FAILURE TYPE	STATUS BASED ON HISTORICAL DATA OF HAZARDS				BRIDGE STATUS
		EARTHQUAKE	CYCLONE	FLOODING	LANDSLIDE	
NH0516B0001	SHEAR FAILURE OF PIER	BRIDGE SAFE	BRIDGE COLLAPSE	BRIDGE SAFE	BRIDGE SAFE	BRIDGE COLLAPSE
	SUPER STRUCTURE UNSEATING	N/A	BRIDGE MARGINALLY SAFE	BRIDGE MARGINALLY SAFE	BRIDGE SAFE	
	SUPER STRUCTURE SHEAR FAILURE	BRIDGE SAFE	BRIDGE MARGINALLY SAFE	BRIDGE SAFE	BRIDGE SAFE	



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

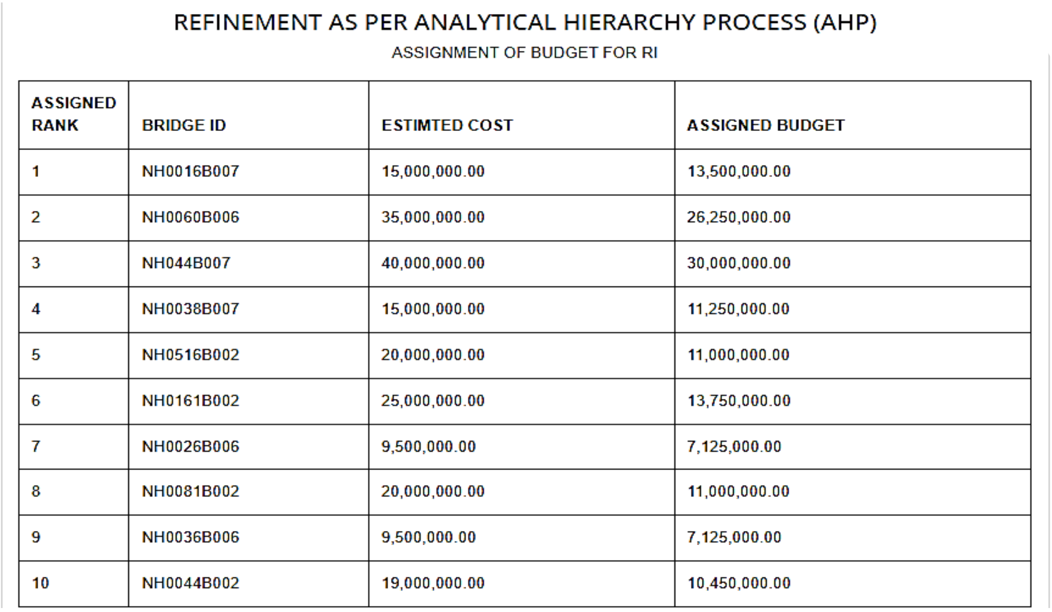
Selected Bridge : 'NH0516B002', 'NH0161B002', 'NH0060B006', 'NH0036B006', 'NH0044B002', 'NH0081B002', 'NH0026B006', 'NH0016B007', 'NH044B007', 'NH0038B007'



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

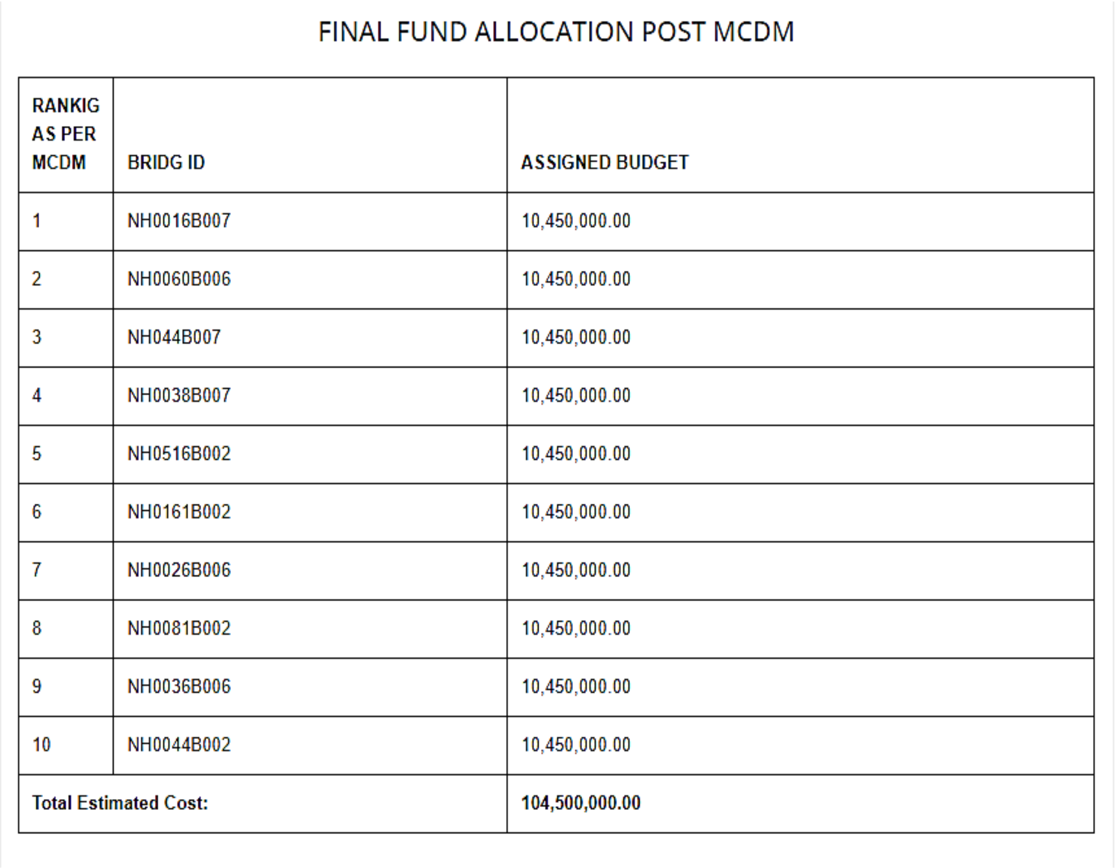


REFINEMENT AS PER ANALYTICAL HIERARCHY PROCESS (AHP)

ASSIGNMENT OF BUDGET FOR RI

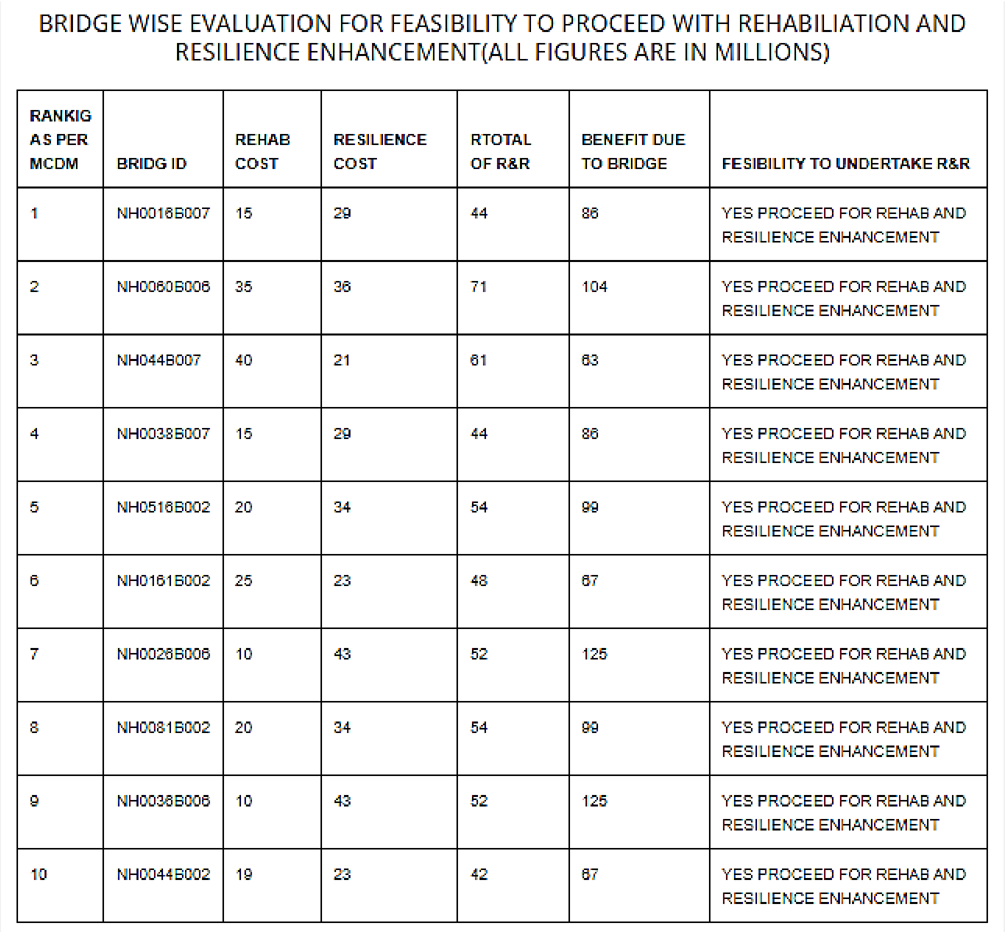
ASSIGNED RANK	BRIDGE ID	ESTIMTED COST	ASSIGNED BUDGET
1	NH0016B007	15,000,000.00	13,500,000.00
2	NH0060B006	35,000,000.00	26,250,000.00
3	NH044B007	40,000,000.00	30,000,000.00
4	NH0038B007	15,000,000.00	11,250,000.00
5	NH0516B002	20,000,000.00	11,000,000.00
6	NH0161B002	25,000,000.00	13,750,000.00
7	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

Post application of AHP, it is critical to decide if the organization should explore the options of enhancing / increasing the budgetary support for rehabilitation of bridges. Enhancement of Bridge Resilience never considered, as a requirement until recently, is gaining importance. With this as focus, GARM evaluates the comparison of enhancing provided budgetary amount. This comparison implemented for each bridge and for the entire set of 10 bridges.



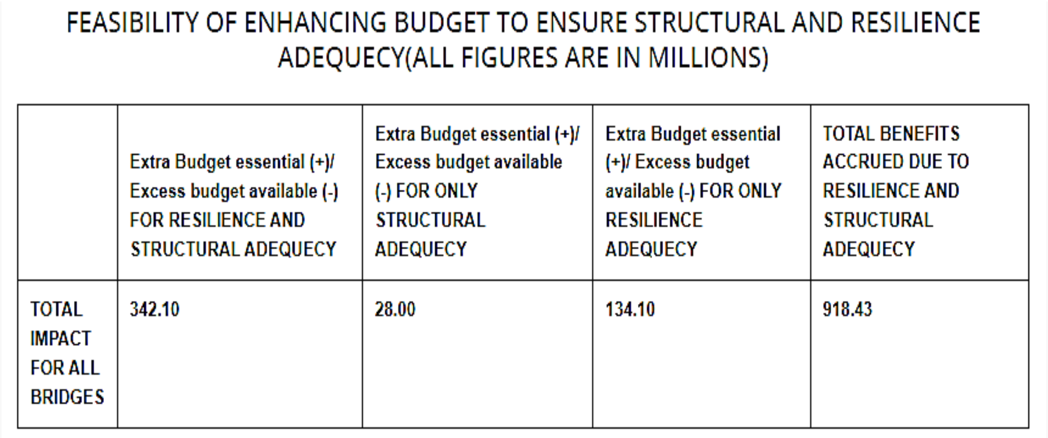
FINAL FUND ALLOCATION POST MCDM

RANKIG AS PER MCDM	BRIDG ID	ASSIGNED BUDGET
1	NH0016B007	10,450,000.00
2	NH0060B006	10,450,000.00
3	NH044B007	10,450,000.00
4	NH0038B007	10,450,000.00
5	NH0516B002	10,450,000.00
6	NH0161B002	10,450,000.00
7	NH0026B006	10,450,000.00
8	NH0081B002	10,450,000.00
9	NH0036B006	10,450,000.00
10	NH0044B002	10,450,000.00
Total Estimated Cost:		**104,500,000.00**



BRIDGE WISE EVALUATION FOR FEASIBILITY TO PROCEED WITH REHABILIATION AND RESILIENCE ENHANCEMENT(ALL FIGURES ARE IN MILLIONS)

RANKIG AS PER MCDM	BRIDG ID	REHAB COST	RESILIENCE COST	RTOTAL OF R&R	BENEFIT DUE TO BRIDGE	FESIBILITY TO UNDERTAKE R&R
1	NH0016B007	15	29	44	86	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
2	NH0060B006	35	36	71	104	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
3	NH044B007	40	21	61	63	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
4	NH0038B007	15	29	44	86	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
5	NH0516B002	20	34	54	99	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
6	NH0161B002	25	23	48	67	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
7	NH0026B006	10	43	52	125	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
8	NH0081B002	20	34	54	99	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
9	NH0036B006	10	43	52	125	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT
10	NH0044B002	19	23	42	67	YES PROCEED FOR REHAB AND RESILIENCE ENHANCEMENT



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

	Extra Budget essential (+)/ Excess budget available (-) FOR RESILIENCE AND STRUCTURAL ADEQUECY	Extra Budget essential (+)/ Excess budget available (-) FOR ONLY STRUCTURAL ADEQUECY	Extra Budget essential (+)/ Excess budget available (-) FOR ONLY RESILIENCE ADEQUECY	TOTAL BENEFITS ACCRUED DUE TO RESILIENCE AND STRUCTURAL ADEQUECY
TOTAL IMPACT FOR ALL BRIDGES	342.10	28.00	134.10	918.43

By integrating data-driven MCDM, continuous monitoring, and strategic resource allocation, risk and resilience management can effectively safeguard the bridge's performance while minimizing future disruptions and financial risks. The integration of Global Analytics for Bridge Management (GABM) and Global Analytics for Resilience and Risk Management (GARM) provides a ground breaking framework for addressing the multifaceted challenges associated with modern bridge infrastructure. By leveraging cutting-edge data analytics, these systems enable detailed evaluations of structural health, balance service life evaluation, and risk and vulnerability index evaluation for natural hazards. GABM and GARM ensure through analysis of each aspect of bridge performance. Their ability to assess and integrate factors like geographical risks, structural parameters, and socio-economic impacts exemplifies a holistic approach to bridge management, laying the groundwork for sustainable and resilient infrastructure solutions. The results, report and insights derived from GABM and GARM highlight the criticality of adopting advanced analytics for long-term infrastructure resilience. Both GABM and GARM offer precise evaluations of distress causes, environmental vulnerabilities, and structural performance, guiding data-driven decisions for maintenance, rehabilitation, and budget allocation. The unique capability to evaluate balance and absolute service life alongside median service life adds a robust layer to the decision-making process. The duo of GABM and GARM ensure interventions are not only effective but also economically and environmentally viable. Furthermore, the Multi-Criteria Decision-Making process in GARM empowers stakeholders to consider structural, financial, and socio-economic factors simultaneously, fostering well-rounded and informed strategies. GABM and GARM represent a significant advancement in bridge management and resilience planning. They address critical challenges such as aging infrastructure, evolving traffic demands, and environmental exposure through real-time monitoring, predictive analytics, and innovative risk management frameworks. They ensure bridges remain functional, safe, and sustainable while optimizing resource utilization and minimizing vulnerabilities. GABM and GARM offer authorities an opportunity to prioritize proactive maintenance, strengthen resilience against natural hazards, and ensure the longevity and socio-economic relevance of bridge infrastructure.

9: RESULTS AND KEY FINDINGS

Research highlights the varying nature and intensity of natural hazards across different regions and their implications on infrastructure, especially bridges[24]. Further, it emphasizes the need for region-specific strategies to mitigate the risks posed by flooding, cyclones, landslides, and earthquakes, which affect over 80% of India.

Key Findings:

1. Regional Hazard Variability

Each region of India is subject to distinct natural hazards, with the North and Eastern regions being the most vulnerable. These areas experience high seismic activity, floods, and cyclones, posing significant challenges to infrastructure resilience. In contrast, the Southern and West Central regions face comparatively lower risks from earthquakes but are still affected by flooding and cyclones. This variability underscores the importance of tailoring resilience strategies based on the specific hazard exposure in each region.

2. Bridge Vulnerability and Damage Patterns

Bridges situated in riverbank areas and low-lying regions are particularly susceptible to flooding and cyclone-induced failures. Across the country, estimates indicate 15-20% of bridges experience varying levels of damage every year, with higher collapse rates observed in regions exposed to multiple hazards.

3. Need for Region-Specific Resilience Strategies

Research emphasizes the importance of region-specific resilience strategies to address the diverse challenges posed by natural hazards. Infrastructure in flood-prone areas requires effective flood control systems, while seismic design is essential in regions vulnerable to earthquakes. In cyclone-prone areas, adopting storm-proof designs will help minimize damage. Furthermore, implementing early warning systems and regular maintenance protocols will reduce the impact of landslides and flooding, particularly in remote and hilly regions.

4. Structural Resilience and BSRN Rating:

The bridge was evaluated against multiple natural hazards (flooding, cyclone, landslide, and earthquake) using a standardized Bridge Structural Rating Number (BSRN) scale ranging from 1 to 5.

- **BSRN 2 to 3:** The bridge structure considered safe across all evaluated hazards, including floods, cyclones, landslides, and earthquakes.

- **BSRN 4 to 5:** At higher stress levels, the bridge shows higher severity of distress and deterioration. At times, this compromises the safety. The bridge needs immediate rehabilitation or retrofit.

This rating system provides key information regarding the structural status of the bridge. Bridge Management system all across the world follow such rating system[25,26]. Linking resilience to BSRN provides a Global approach.

Image Credit 04: US Geological Society (San Francisco Oakland Bay Bridge)

5. Failure Mode Analysis:

Three principle modes of failure in any element observed to result in majority bridge collapse. Historical narratives also state that the bridge collapse show higher probability of cascading effect under these three modes of element failure. The three modes are:

A) Shear failure of pier/ substructure
B) Unseating of superstructure
C) Shear failure of superstructure.

These three modes of element failure analyzed in the Resilience Evaluation Module of Global Analytics for Bridge Management [GABM]. Each mode analyzed based on various geometrical dimensions of the bridge using standard design philosophy. For bridges, which are old deteriorated; the analysis takes into account the BSRN and the magnitude of distress within the element. Element with highest probability of failure [showing very severe distress] is then subjected to analysis. The result of the element then projected onto adjoining elements to evaluate the probability of cascading failure[27,28]. The result is the probability of this failure and reported in three categories.

- **A)** High probability of Survival due to bridge being SAFE
- **B)** Marginal probability of Survival due to bridge being Marginally SAFE
- **C)** High Probability of Collapse due to bridge being UNSAFE.

6. Bridge Structural Assessment: Input Parameters Overview

To ensure the safety, durability, and optimal performance of a bridge, it is essential to collect comprehensively all-important parameters, which contribute to the overall stability of the bridge structure. These inputs cover every significant structural component and geometric feature of the bridge, including bridge geometry, substructure, superstructure, and deck details[29]. Inputs also need to include basic details regarding the location of the bridge. For this, the critical aspect relating to Earthquake zone and the zone [North Eastern, West-Central, Southern region] of the bridge collected. Standardized format of inputs collected from users to access and manage the bridge efficiently given below.

When the Resilience module used for old deteriorated bridges, the BSRN parameters for Deck, Superstructure, Substructure and Foundation taken into consideration.

For new bridges, the designer can use Resilience Evaluation Module by inputting the required designed values of the bridge design including the geometry and locational details. The Module will provide the result in terms of the Probability of Survival or Collapse[30,31]. This result evaluated based on the location of bridge with respect to the zone and the Ratings for natural hazards take into account the dynamism in severity and frequency.

The result categories the bridge as

- **A)** Bridge Safe meaning bridge has high probability of Survival.
- **B)** Bridge Marginally Safe meaning bridge has marginal probability of Survival.
- **C)** Bridge Collapse meaning the bridge high probability of collapse.

Bridge Assessment Input Parameters

Parameter Category	Parameter	Parameter Category	Parameter
Location and Hazard Details	Location of Bridge	Substructure Details	Number of Piers Supporting One Location

	Earthquake Zone		Shape of Pier
Bridge Geometry	Length of Bridge		Dia/Width of Pier
	Number of Spans		Depth of Pier
	Maximum Span Length		Shear (Helical) Rebar Dia.
	Number of Lanes		Spacing of Shear Rebars
Parameter Category	Parameter	Parameter Category	Parameter
Superstructure Details	No. of Girders /Beams per Span	Deck Details	Thickness of Deck Slab
	Shape of Girder/ Beam		No. of Bearings at One Junction
	Depth of Girder/ Beam		Type of Bearings
	Width of Girder/ Beam	Reinforcement percentage	Reinforcement percent in superstructure
	Secondary Rebar Dia.		Reinforcement percent in substructure
	Secondary Rebar Spacing		

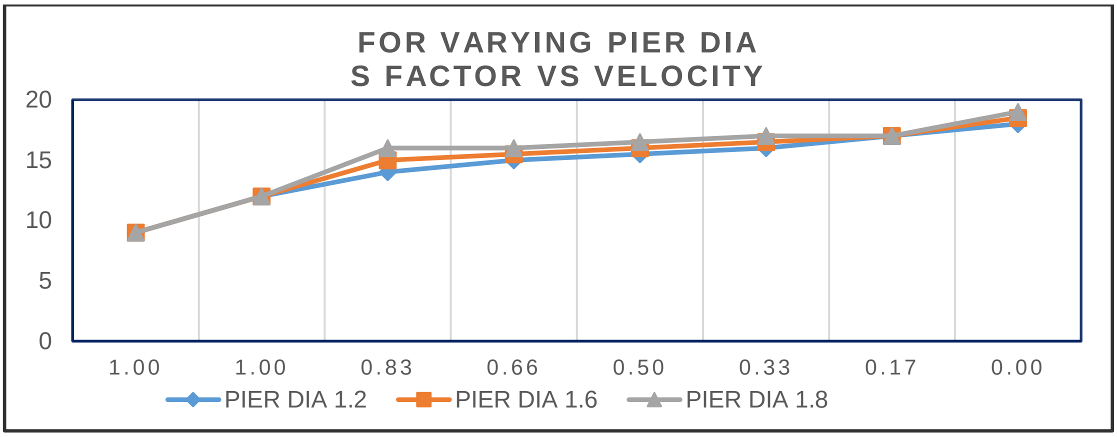
Table 8: Resilience Evaluation Module Input screen

The collection of these standardized input parameters ensures that the bridge design and maintenance meet regulatory and performance standards. It helps engineers predict performance under various conditions, such as seismic activity and traffic loads, while also identifying potential failure points in the substructure and superstructure. The considered forces due the natural hazards are higher [to account for higher severity] than those considered in normal design calculation. Hence, this evaluation is futuristic in its approach.

Typical results for a standard bridge geometry presented herein under. These results indicate that Pier dimension and shape dictate the probability of shear failure of bridge substructure. Similarly, the dimensions and shape of girder/ superstructure dictate the toppling and unseating failure of the bridge. The most critical aspect is the height of bridge for all three modes of failure. Velocity of floodwater and landslide debris determine the probability of survival.

	Circular Pier of diameter varying from 1.2 to 1.8 meters. Height of pier 8 meters, Concrete M40 and shear rebar 18mm at 150 mm C/C, ABSRN>3.5							
Pier Dia	**Velocity of water flow**							
1.2	9	12	14	15	15.5	16	17	18
1.6	9	12	15	15.5	16	16.5	17	18.5
1.8	9	12	16	16	16.5	17	17	19
Sfactor	1.00	1.00	0.83	0.66	0.50	0.33	0.17	0.00
	All Safe	All Safe	2 Safe,1 Mar	1 Safe, 2Mar	3 Marginal	2Mar, 1 Colla	2Colla,1Mar	All Collapse

Table 9: From All Safe to All Collapse as velocity increases [Circular Piers]

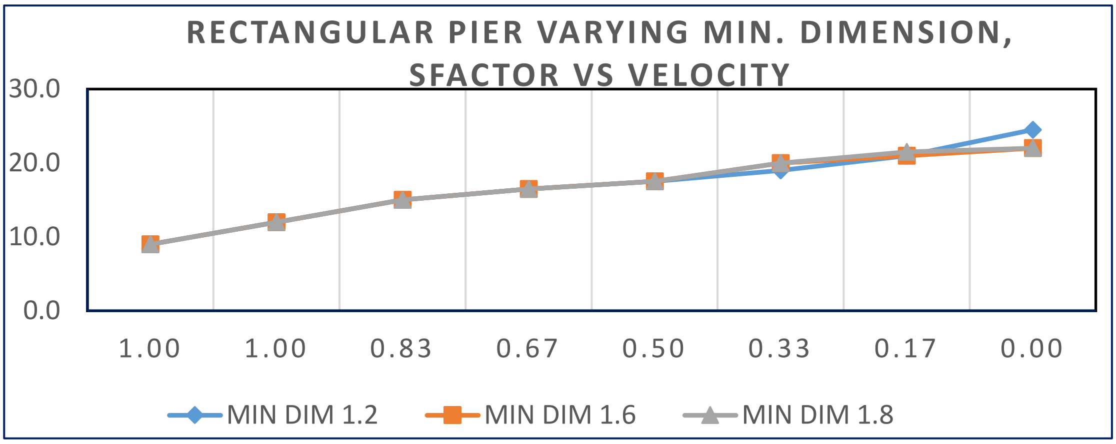


Graph 1 for Table 9: From All Safe to All Collapse as velocity increases [Circular Piers]

Pier Shape (Rectangular Pier): The Bridge spans 100 meters in length with a maximum span of 20 meters between piers. It accommodates four traffic lanes, supported by eight rectangular girders, each with a depth of 2.5 meters and a width of 1.5 meters. Single rectangular piers/ span [dimensions of 1.25 X 14 meters and a height of 15 meters]. Given the bridge's location in Earthquake Zone 4. Analysis show that change of shape renders the bridge safe in all zone for all natural hazards.

	Rectangular Pier of diameter varying from min dimension 1.2 to 1.8 meters. Width same at 5 M, Height of pier 8 meters, Concrete M40 and shear rebar 18mm at 150 mm C/C, ABSRN>3.5							
Pier Dia	**Velocity of water flow**							
1.2	9.0	12.0	15.0	16.5	17.5	19.0	21.0	24.5
1.6	9.0	12.0	15.0	16.5	17.5	20.0	21.0	22.0
1.8	9	12	15	16.5	17.5	20	21.5	22
Sfactor	1.00	1.00	0.83	0.67	0.50	0.33	0.17	0.00
	All Safe	All Safe	2 Safe,1 Mar	1 Safe, 2Mar	3 Marginal	2Mar, 1 Colla	2Colla,1Mar	All Collapse

Table10: From All Safe to All Collapse as velocity increases [Rectangular Piers]

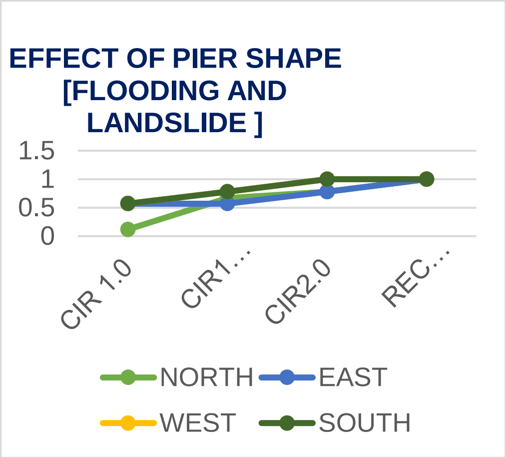


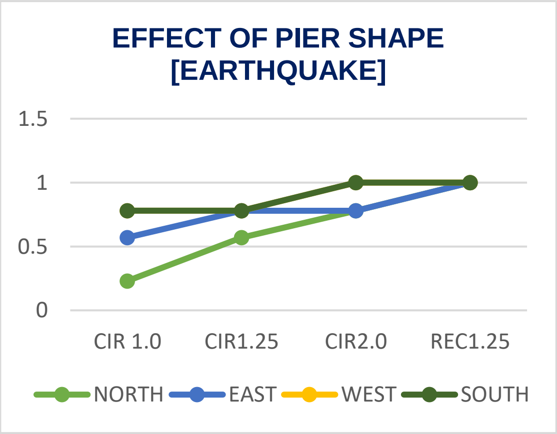
Graph 2 for Table 10: From All Safe to All Collapse as velocity increases [Rectangular Piers]

Pier Shape (Circular Pier): Table 8 presents the hazard assessment of a bridge with circular piers. It provides an assessment of the bridge's structural performance under different natural hazards—flooding, cyclones, landslides, and earthquakes—categorized by region. The table evaluates probability of failures under three modes mentioned above, offering insights into the bridge's safety in varying conditions. **Refer Table 8**

The bridge features 4 circular piers/span with a diameter of 1.25 m and a height of 15 m. It spans 100 meters in total length, with a maximum span of 20 m between piers. The deck supports 4 traffic lanes supported by 8 girders/span, each with a depth of 2.5 m and a width of 1.5 m. The bridge lies within Earthquake Zone 4. The BSRN assigned for this analysis ranges between 3, 4, and 5.					
Failure Type	Region	Flooding	Cyclone	Landslide	Earthquake
Shear Failure of Pier	North	Collapse	Safe	Collapse	Safe
	East, West, South	SAFE			
Super Structure Unseating & Super Structure Shear Failure	All Regions Safe				

Table 11: Structural Failure Assessment under Various Hazards across Regions [For Circular Piers]





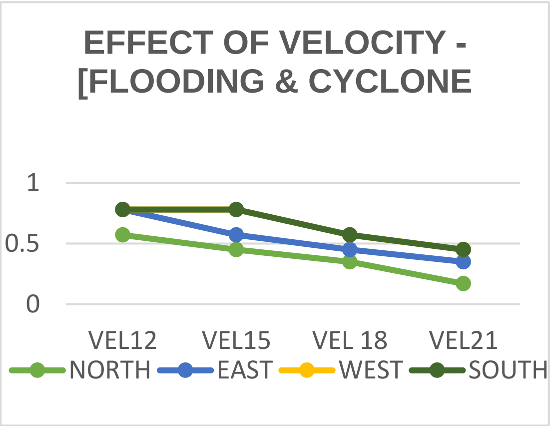
Velocity Variation (Circular Pier): The Bridge spans 100 m with a maximum span of 20 m and supports 4 traffic lanes. It is designed with piers following a shape index of 3, a height of 15 m, and a diameter of 1 m. The structure includes 8 girders, each 2.5 m deep and 1.5 m wide. The bridge falls under Earthquake Zones 5. It maintains a minimum velocity of 14 kmph, with the BSRN rating ranging between 3, 4, and 5.

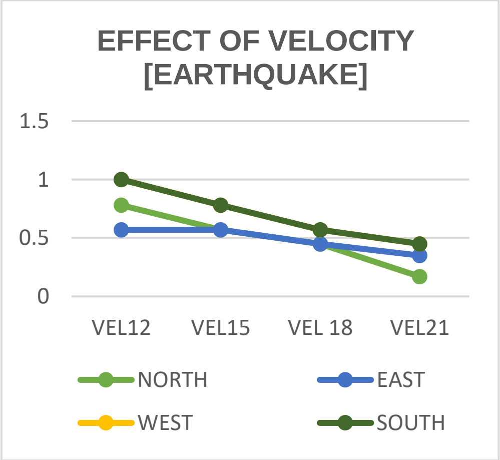
The bridge demonstrates safe to moderately safe performance across most regions and hazards, with exceptions of pier collapse in the North under flooding, cyclone, and earthquake conditions.

The bridge spans 100 m with a maximum span of 20 m, experiencing a 20% increase in velocity, with a minimum velocity exceeding 16 kmph. It features 4 traffic lanes supported by 8 girders, each 2.5 m deep and 1.5 m wide. The piers, with a diameter of 1 m and a height of 12 m, follow a shape index of 3. Located in Earthquake Zones 5, with a BSRN rating between 3, 4, and 5.					
Failure Type	Region	Flooding	Cyclone	Landslide	Earthquake
Shear Failure of Pier	North	COLLAPSE		SAFE	Collapse
	East				M Safe
	West				SAFE
	South				
Super Structure Unseating	ALL REGIONS SAFE				
Super Structure Shear Failure	North	Collapse			M Safe
	East, West, South	M SAFE			SAFE

Table 12: Velocity Variation Assessment under Various Hazards across Regions [For Circular Piers]

The below hazard assessment evaluates the bridge's performance across various natural disasters—flooding, cyclones, landslides, and earthquakes—categorized by failure type and region. The BSRN (Bridge Structural Rating Number) assigned for this analysis ranges between 3, 4, and 5.



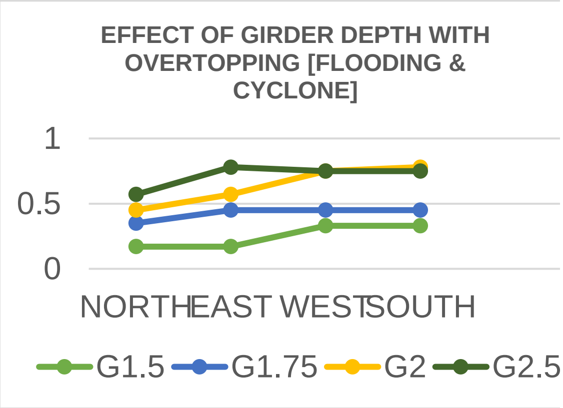


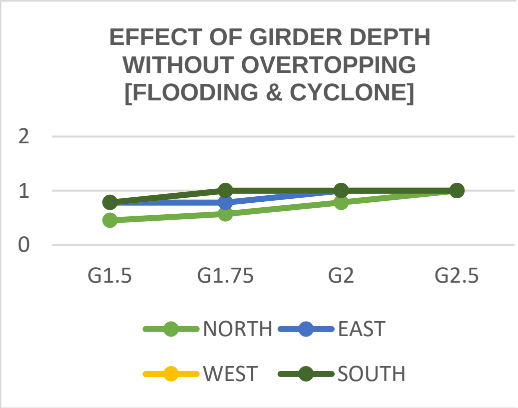
This comprehensive assessment confirms that the bridge structure remains safe under all evaluated hazards across the North, East, West, and South regions.

The bridge spans 100 m with a maximum span of 20 m, accommodating 4 traffic lanes. It features 8 girders, each 1.5 m deep and 1 m wide, supported by piers with a diameter of 1 m and a height of 15 m. The structure lies in Earthquake Zones 5, with velocities ranging from a minimum of 12 kmph to a maximum of 23 kmph. The BSRN rating varies between 3, 4, and 5.

Failure Type	Region	Flooding	Cyclone	Landslide	Earthquake
Shear Failure of Pier	North	Collapse	Collapse	Safe	M Safe
	East	M SAFE		Safe	
	West				
	South				
Super Structure Unseating	ALL REGIONS SAFE				
Super Structure Shear Failure	North	Collapse	Collapse		Safe
	ALL REGIONS SAFE				

Table 13: Girder Variation Assessment under Various Hazards Across Regions [For Rectangular Piers]

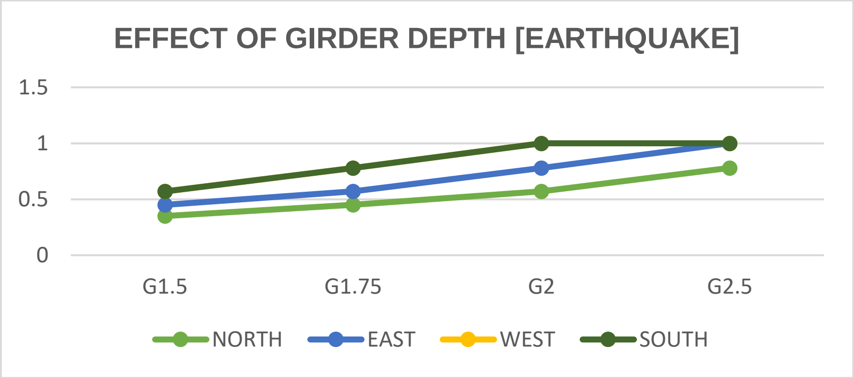




Girder Dimension Changes (Circular Pier):

The bridge spans 100 m with a maximum span of 20 m, supporting 4 traffic lanes. It features 8 girders with dimensions of 1.5 m in depth and 1 m in width. The piers, shaped according to index 3, stand 15 m high with a 1-m diameter. Located in Earthquake Zone 5, the structure has a BSRN rating between 3 and 5. The minimum velocity on the bridge is 16 kmph.

The bridge faces pier shear failure during flooding and cyclones, partial safety under earthquakes, moderate safety for superstructure unseating in the North, and varying risks of superstructure shear failure across regions.



10: DISCUSSION-CHALLENGES IN RESILIENCE

Building resilient infrastructure, especially bridges, presents several challenges due to the complex interplay of natural, structural, and operational factors:

- Geographical and Environmental Constraints:
- Material Durability and Maintenance:
- Design and Engineering Limitations:
- Uncertainty in Climate Change Impacts:
- Policy and Funding Gaps:

One of the primary challenges is accounting for unpredictable environmental hazards, such as earthquakes, floods, and landslides, which vary across geographic zones. Ensuring structural durability while adhering to evolving design standards adds further complexity, particularly when balancing cost-efficiency with safety[32,33].

Usage of MCDM along with Resilience Evaluation majorly absolves all the above challenges. MCDM usage is transparent. The Data essential is available within BMS and provides the user organization to monitor which parameter given importance at a particular period.

Image Credit 05: Tracy Garstka (Big Dam Bridge over the Arkansas River)

Another significant challenge lies in managing material degradation over time, such as corrosion of reinforcement and wear on bearings, which can compromise performance without timely intervention. Adapting designs to accommodate increased traffic loads and climate changes requires proactive planning and continuous monitoring through advanced technologies.

Operational challenges also arise from limited resources for inspections and maintenance, making it difficult to schedule timely repairs. Bridge Management's focus on structural status and fund allocation only post occurrence of distress will need changes. Mono-Criterion Decision-Making focus within Bridge Management systems [BMS] will need inclusion of Risk assessment. Risk assessment's integration preceded start of Resilience evaluation. Financial due diligence rarely exists within engineering teams, integration of Life Cycle Cost Analysis and inclusion of Socio-Economic aspects within BMS created the most appropriate platform to shift to Multi-Criterion Decision-Making process for fund allocation within BMS.

Essentially required coordination among stakeholders, including government bodies and contractors, will provide critical decisions and actions[34,35]. A holistic approach that integrates robust design, predictive maintenance, and policy support to achieve sustainable and resilient infrastructure will enhance Resilience.

11: CONCLUSION:

Dynamism in natural hazards occurrences due to ever increasing severity and reduction in frequency of such high severity events results in a complex scenario. Bridges designed for forces as per design standard have insufficient force resisting capacity to account for the dynamism. This at times results in failure of bridge elements causing collapse of entire bridge structure.

Classically, Bridge Management restricted to fund optimization with a very sharp focus on distress in bridges. Bridge Management lacked a proactive approach and did not consider the bridge as a candidate for fund allocation if distress was absent. This is not appropriate approach to ensure and enhance resilience.

Resilience in bridges need the bridge to sustain over longer period in changing scenarios due to climate change and dynamism of natural hazards. Research designed the approach to achieve and enhance Resilience. For simplicity, the research focused on bridges in India. Replicating the designed approach for any, other country or region is feasible. Approach adopted division of India into four broad regions based on its severity and historical narrative relating the frequency of occurrences of natural hazards. For each region, natural hazards rating evaluated. This ensured the diversity observed in natural hazards considered and accounted. Vulnerability of bridges depends on the region where the bridge exists along with the bridge geometry, material and the structural status of the bridge[36]. Evaluation of vulnerability essentially takes into consideration all the above factors. Risk index evaluation succeeds vulnerability evaluation.

The need for a shift from Mono-Criterion Decision-Making process to a multi-criteria process needed. This need arises from the growing importance of ensuring the resilience of the entire logistics network. Bridges constitute an important contributory factor. Resilient infrastructure recognized as one of the critical pillars of sustained growth and development of the region. This translates to the overall growth and development of the country. Resilient bridge inventory becomes critical from the standpoint of the socio-economic growth and stability. In view of the serious threat to bridges due to dynamism of natural hazards, it is critical that mono-criterion decision-making process within Bridge management needs to undergo changes. Multi-Criterion Decision-Making [**MCDM**] process for fund allocation is necessary. Global Analytics for Bridge Management deploys Resilience Evaluation Module and evaluates the survival probability. Then the entire set of bridge inventory within the network subjected to MCDM where four criterion [Structural status, Risk assessment, Financial impact, Socio-Economic impact] decide fund allocation. Using MCDM ensure Resilience is accounted for in a proactive manner.

Research underscores the critical need to enhance the resilience of bridge infrastructure globally amidst the increasing frequency and intensity of natural hazards exacerbated by climate change. With the dynamism of natural disasters, rendering traditional design practices inadequate, a paradigm shift is essential. The comprehensive assessment of regional vulnerabilities emphasizes the importance of adapting bridge designs to withstand a variety of hazards, ensuring the safety and functionality of these vital structures. By integrating advanced data analysis, risk modelling, and tailored engineering assessments, Resilience Evaluation Module of Global Analytics for Bridge Management, provides a robust framework for developing resilience-enhancing strategies. The findings advocate for immediate action. Implementation will safeguard bridges and bolster the socio-economic fabric of communities dependent on reliable transportation networks.

The basic bridge geometry and material properties and the structural status of the bridge structure dictate the behaviour of the bridge. Considering these parameters, the next step is evaluation of the probability of bridge element failure[37]. Evaluation takes into account the dynamism of natural hazards considering incremental severity of natural hazards.

Various geometrical parameters like shape and size of the substructure and superstructure hold the key to this behavioural analysis. Bridges with wide rectangular piers show more resilience as compared to multiple circular piers of smaller diameter.

Girder dimensions also define the resilience. When over-topping of bridge does not occur, [height of bridge being greater than the flood height] the dimensions of bridge superstructure determines the resilience in bridge. When over-topping occurs, the flood velocity determines the bridge resilience.

During flooding wherein over-topping of bridge occurs, the velocity of water decide the fate of the bridge, irrespective of the design philosophy. During flash floods, velocity recorded are greater than 21kmph. Survival of bridge under such high velocity is very difficult. When landslides accompany floods or when landslides triggered by floods, the equation changes. Velocity of 18kmph with sedimentation over 50% makes it difficult for survival of bridges. Presence of curvature just prior to bridge location increases the potential of scour. Scour lowers the survival boundary to a velocity of 16kmph.

Resilient bridges ensure sustainable logistics network. Sustained network acts critically to ensure natural hazard occurrence do not turn to disaster or calamity. Resilient Bridges consolidate Disaster Risk Reduction[38]. Researched material serves as a vital knowledge base, guiding future infrastructure development in a rapidly changing climate, and highlights the urgent need for resilient designs to mitigate the long-term impacts of natural disasters on India’s infrastructure.

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