RESILIENCE IN BRIDGES: DEMYSTIFIED

RESEARCHED AND CONCEPT BY

UBMS RESEARCH GROUP

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ABSTRACT:

Bridges are vital enablers of connectivity, stability, and socio-economic growth, yet their resilience is increasingly threatened by aging, deterioration, and the growing frequency of natural hazards. Their survival is critical, as resilient bridges ensure uninterrupted mobility, timely rescue operations, and efficient delivery of aid during disasters, directly influencing community safety and recovery. Conventional bridge management, largely reactive focused on symptoms, is insufficient to meet these dynamic challenges.

The authors profess proactive, resilience-based framework that integrates Global Analytics for Bridge Management (GABM) & Global Analytics for Risk and Resilience Management (GARM). GABM systematically evaluates hazard exposure, deterioration, and vulnerability, while GARM applies Multi-Criteria Decision-Making (MCDM) to balance structural, financial, and socio-functional priorities. The framework develops a Priority Index to identify high-risk structures, optimize rehabilitation strategies, and guide timely interventions.

Findings reveal that resilience-focused investments enhance bridge performance under stress but also minimize life-cycle costs, service disruptions, and socio-economic losses. Embedding resilience benchmarks into bridge management policy, supported by innovative financing tools such as Resilience Bonds and CSR funds, provides a scalable, cost-effective pathway to safeguard infrastructure. The GABM–GARM framework redefines bridges as socio-economic lifelines, essential for sustainable development in hazard-prone regions.

INTRODUCTION:

Bridges are indispensable lifelines for modern societies, providing seamless connectivity that supports daily activities, sustains commerce, and fosters social and economic development. They link towns and cities, enable people to access workplaces, schools, hospitals, and recreational facilities, and ensure the efficient movement of goods and services. Beyond economic contributions, bridges play a pivotal role during emergencies, where their survival can determine the effectiveness of rescue and relief operations. Even a short disruption in connectivity can escalate the consequences of natural hazards, transforming manageable events into large-scale calamities. Thus, bridges remain the silent yet critical enablers of stability, prosperity, and sustainable growth.

Like all man-made structures, bridges inevitably age and deteriorate. While routine wear and tear may manifest as visible signs such as cracks, corrosion, and spalling, much of the distress often progresses silently until significant damage occurs. Traditionally, bridge management has been reactive—rehabilitation or repair measures are undertaken only after symptoms become severe. This approach, akin to seeking medical help only in advanced stages of illness, exposes infrastructure and communities to heightened risks. In contrast, a proactive approach focuses on early detection of vulnerabilities, accurate estimation of forces acting on bridge structures, and timely implementation of rehabilitation or strengthening strategies to extend service life and enhance resilience[1].

The urgency of adopting proactive bridge management is amplified by the increasing frequency and severity of natural hazards such as floods, earthquakes, cyclones, and landslides. Design codes and guidelines, often based on statistical recurrence of once-in-a-century events, are struggling to remain relevant as such events now occur within decades or even years, often with higher intensities. This dynamism challenges conventional design philosophies and highlights the critical need for innovative frameworks that account for evolving risks.

In this context, resilience emerges as the cornerstone of sustainable bridge management. Resilience is not only the capacity of a bridge to withstand hazards but also its ability to adapt and recover quickly, minimizing disruptions and socio-economic losses. Advanced frameworks such as the Global Analytics for Bridge Management (GABM) and the Global Analytics for Risk and Resilience Management (GARM) offer comprehensive solutions to these challenges. GABM enables systematic quantification of hazard exposure, deterioration, and vulnerability, while GARM incorporates Multi-Criteria Decision-Making (MCDM) to balance structural, financial, socio economic, and functional priorities. Together, these tools facilitate data-driven, risk-informed, and cost-effective decisions, shifting bridge management from reactive spending to proactive, value-based investments.

By integrating predictive analytics, resilience scoring, and value engineering (Value-E), this approach not only optimizes resource allocation but also ensures bridges remain robust, sustainable, and capable of serving future generations[2,3]. Ultimately, embedding resilience into bridge asset management transforms infrastructure planning into a forward-looking strategy—safeguarding lives, supporting economies, and strengthening communities in the face of growing uncertainty.

Gambling with Nature a known losing Strategy. Unless we switch from Gambling with Nature to investing in RESILIENCE, the mounting weight of Losses will eventually cause the house of cards to collapse

QUOTE by: ARIS PAPADOPOLOS
Book "ResilieNomics – Value in an age of Disaster" 2024

OBJECTIVES:

The overarching goal of this study is to design a structured, scale-able, and resilient bridge management framework that enables technically sound and financially viable decisions for enhancing infrastructure resilience to natural hazards. The approach is rooted in assessing vulnerability to define resilience enhancement procedures, followed by financial due diligence to ensure the practicality and affordability of these interventions. This methodological alignment provides the backbone of a national resilience strategy grounded in data, performance, and cost-efficiency.

To achieve this, the study follows a step-wise, integrated approach with the following specific objectives[3]:

Identify and Classify Vulnerability - Evaluate bridge exposure to floods, earthquakes, landslides, and cyclones using historical data, hazard maps, and climatic zones to create a regional hazard classification matrix.

Develop a Multi-Dimensional Resilience Framework - Incorporate structural condition, hazard frequency/intensity, functional criticality, recovery potential, and socio-economic impact to produce a resilience index and scoring system.

Integrate Financial Analysis - Link targeted resilience measures (e.g., seismic retrofitting, flood-resilient foundations) with cost implications, ensuring technical justification and affordability[4].

Prioritize Bridges for Intervention - Apply the GABM–GARM framework to calculate costs, benefits, life-cycle gains, and value engineering metrics, ranking bridges by return on resilience (RoR) and long-term value.

Propose a Scalable National Methodology - Use MCDM to generate ranked intervention lists, ensuring resources target high-risk, high-impact structures.

Develop a Replicable National Resilience Framework - Ensure adaptability across regions, hazards, and infrastructure types, aligned with evolving climate data and policy goals. This protocol defines the boundaries and eligibility of any bridge to be provide with proactive funding based on financial due diligence[5].

GENERATED FROM GABM
R & D BY UBMS RESEARCH GROUP

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

Selected Bridge : 'APNH016B0010', 'ASNH17B007', 'BRNH022B005', 'GJNH048B0014', 'HPNH005B002', 'KANH704B0012', 'MLMGNH006B008', 'PBNH005B003', 'TNNH016B009', 'UKNH007B001'

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	HPNH005B002	3.1	34,200,000.00	34,200,000.00	YES

FINAL FUND ALLOCATION POST MCDM

RANKING AS PER MCDM	BRIDGE ID	ASSIGNED BUDGET
1	HPNH005B002	20,377,500.00
2	PBNH005B003	20,377,500.00
3	MLMGNH006B008	20,377,500.00
4	APNH016B0010	20,377,500.00
5	KANH704B0012	20,377,500.00

TOTAL BENEFITS ACCRUED CONSISTS OF:

a. Direct Benefit

b. Indirect Benefit

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

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

METHODOLOGY:

Bridge Evaluation and Data Collection:

Bridges were selected for assessment based on their physical condition, functional importance, and role in regional connectivity, including support for transport corridors, economic activity, and emergency response. Guided by the Global Analytics for Bridge Management (GABM) framework, data collection covered material condition, structural behavior, maintenance history, and exposure to geospatial hazard variables.

Key evaluations included:

1) **Material Condition Assessment -** Visual inspections and non-destructive tests identified deterioration (cracks, corrosion, scaling, spalling), converted into a Bridge Structural Rating Number (BSRN) to pinpoint weak components.

2) **Structural Integrity Check -** Analysis of load paths, stress points, and deformation under design and extreme loads.

3) **Hazard Vulnerability Mapping -** Geo-spatial and historical data identified floodplains, seismic zones, landslide slopes, and hydrological stressors.

This comprehensive dataset enabled vulnerability scoring and risk modeling within the GABM-GARM framework, supporting resilience-based prioritization.

4) **Multi-Criteria Decision-Making (MCDM):**

The Global Analytics for Risk and Resilience Management (GARM) methodology applied a customized Multi-Criteria Decision-Making (MCDM) model to prioritize bridge interventions for maximum resilience impact[6,7].

Key criteria evaluated through GARM included:

a. **Structural Adequacy -** Compliance with national codes and fatigue-life projections.

b. **Remaining Service Life -** Estimated through GABM deterioration modeling. Balance service life, Absolute Balance service life and Median Service Life are all evaluated. Median Service Life evaluation helps us to decide the effectiveness and efficiency of implementing remedial interventions.

c. **Hazard Risk Score -** Based on hazard exposure, frequency-intensity data, and fragility functions.

d. **Socio-Economic Disruption Index -** Measured the effect of potential failure on communities, trade, logistics, and essential services.

e. **Resilience-Cost Ratio -** Calculated long-term returns on resilience investments using benefit-cost analysis.

Each factor was weighted for its role in risk reduction, with scores normalized into a Priority Resilience Index to guide transparent and effective resource allocation[8,9].

f. Cost Analysis:

A dual-component costing model under GABM-GARM was used to distinguish between conventional rehabilitation and resilience-focused investments, improving transparency, funding prioritization, and alignment with long-term risk mitigation goals.

a. Rehabilitation Cost (GABM-centric)

Focuses on restoring operational standards without significantly improving hazard resilience. Activities include structural repairs (e.g., crack repair, corrosion treatment, deck resurfacing), functional upgrades (e.g., drainage, lighting, railings), and preventive maintenance (e.g., waterproofing, sealing joints). GABM uses deterioration data and predictive analytics to determine minimum investment for safe service restoration, though vulnerability to future hazards remains.

b. Resilience Enhancement Cost (GARM-centric)

Targets long-term durability and hazard adaptation. Measures include seismic strengthening, flood/scour protection, high-performance materials, redundancy features, and IoT-enabled monitoring systems. While capital-intensive, GARM applies probabilistic risk models to demonstrate life-cycle cost savings through avoided damage and faster recovery.

c. **Strategic Implications:**

This cost segregation allows policymakers to compare short-term savings with long-term resilience benefits, justify higher upfront spending, secure targeted funding, and design multi-tier financing strategies for hazard-prone infrastructure.

Benefit Estimation

A life-cycle benefit analysis under the GARM framework evaluated both tangible and intangible returns from resilience-focused bridge investments over their operational life.

a. Direct (Tangible) Benefits - Immediate and measurable:

1. **Reduced Vehicle Operating Cost (VOC): Improved pavements** and restored connectivity lower rolling resistance, fuel use, and maintenance needs.
2. **Time Savings (VOT):** Eliminating detours and delays improves transport efficiency, especially during peak hours or emergencies.
3. **Lower Maintenance Burden:** Advanced materials and reinforcements reduce repair frequency and emergency costs.
4. **Fewer Service Interruptions:** Resilient designs maintain operations even during moderate hazard events.

b. Indirect (Intangible) Benefits - Longer-term socio-economic and environmental impacts:

1. **Hazard Impact Mitigation:** Quick recovery post-disasters reduces economic loss and human hardship.
2. **Enhanced Connectivity:** Critical links for rural/remote areas improve access

to work, education, healthcare, and markets.

3. **Economic Growth**: Reliable infrastructure stimulates investment, trade, tourism, and agriculture.

4. **Climate Adaptation Co-Benefits**: Greener designs via sustainable materials, modular construction, and energy efficiency.

5. **Institutional Credibility:** Demonstrated resilience attracts national/international funding.

a) Benefit-Cost Integration:

1. **BCR:** Net benefits over project costs.

2. **NPV:** Discounted value of future gains.

3. **Resilience Payback Period:** Time to recoup investment via avoided losses and enhanced functionality.

Integrating GABM (baseline performance) with GARM (risk management) shifts planning from reactive to resilience-first, where higher initial costs are offset by safer, sustainable, and economically viable infrastructure in the face of hazards and climate variability[10].

IMPACT OF RESILIENCE IN BRIDGES

Resilience of a bridge is not just about it's structural integrity. It's about its ability to withstand shocks and stresses both natural and man made a resilient bridge can withstand earthquakes floods and other natural hazards. It can also withstand the wear and tear of daily use and the test of time. When bridges are resilient, communities thrive. Businesses can operate with confidence knowing that their goods and services can flow freely. People can commute to work, access health care and visit loved ones without disruption.

Emergency services can respond quickly and effectively when disaster strikes. Resilient bridges are essential for maintaining a healthy and vibrant society. They provide a sense of security and stability. Knowing that essential life lines remain intact even in the face of adversity this sense of stability is crucial for economic investment, social cohesion and overall well being. It also enables faster rescue operations resulting in saving lives during and post natural hazard occurrence. Resilience in bridges is not a utopian concept. It is achievable goal[11].

Previously absence of knowledge relating to the behavior of deteriorating bridges during natural hazard occurrences, resulted in inability of the inspection and testing teams to determine the requirements of precautionary steps to be adopted. Today, with available knowledge base, it is feasible to take proactive steps to enhance and establish resilience[12].

FACTORS AFFECTING RESILIENCE IN BRIDGES

Multiple factors influence and affect the resilience of bridge. Principal factors influencing are the structural design, load capacity, material properties, environmental conditions, and maintenance strategies. For ensuring the longevity and reliability of bridge structures, understanding these factors becomes crucial, particularly in regions prone to natural hazards such as earthquakes, floods, landslides, and cyclones[13,14].

1. Structural Design and Load Capacity:

Resilience in bridge significantly depends on its structural configuration, including but not limited to the number of spans, pier design, girder dimensions, and reinforcement percentages. Bridges with well-designed load-bearing elements, with typically rectangular piers and I-shaped girders, are more capable of withstanding external forces. The dimension of piers, along with that of substructure, the reinforcement details, play a key role in distributing loads efficiently and preventing failures. Failure is primarily due to shear failure of piers, toppling and or overturning of girders/ beams. Most of the bridge collapses recorded have been majorly due to the three modes stated above. Scour also can accelerate failure.

2. Material Strength and Durability:

Choice of material plays a very crucial role in ensuring resilience. Concrete and steel structures can attain resilience when certain precautions are implemented in the design stage. Providing for least permissible dimensions, normally result in economical construction but does not essentially result in resilience. The selection of high-quality construction materials [reinforced concrete, high-strength steel, and corrosion-resistant coatings] coupled with proper dimensions, directly affects bridge resilience. Proper material choices contribute to improved load-bearing capacity, reduced maintenance needs, and extended service life.

3. Regular Inspection and Maintenance:

Even the most well-designed bridges require continuous inspections, monitoring and maintenance to remain resilient over time. Routine inspections, structural health monitoring systems, and timely repairs help detect and arrest early signs of distress, preventing catastrophic failures. Analysis indicate that as deterioration in bridges increases, the resilience in bridges gets compromised. Bridges which are maintained results in the average Bridge

Structural ratings below 3.5. Such bridges show very low probability of collapse or failure, implying higher resilience. Implementing proactive maintenance strategies ensures that bridges remain safe and operational under varying environmental conditions.

To illustrate the impact of four main hazards on the bridge, we state the impact of each of those hazards separately in the image below. Red color indicates Collapse, Blue indicates Marginally Safe and Green indicates Safe.

Bridges located in North region indicate that for BSRN values above 4, probability of collapse is very high. Similarly for all other regions, this high probability of collapse is observed only for BSRN values of 5. In every region probability of survival is observed for BSRN value below 2 barring South region where the BSRN value is below 3. Between the 2 area of Collapse and Safe lies the Marginally Safe area.

1. Seismic Resilience and Earthquake Impact

Bridges located in higher seismic zones require advanced engineering solutions to mitigate earthquake-induced forces. Shear failure of piers and superstructure displacement are common risks in earthquake-prone areas. Adequate care during design is normal, reinforcement detailing should account for seismic forces. Shear reinforcement spacing, and type of bearing enhances the bridge's ability to absorb seismic shocks, reducing the likelihood of structural collapse. Additional considerations are required to provide for the dynamism of frequency and severity of earthquake[15]. Analysis indicate:

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

2. Flooding and Hydraulic Forces

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

- **a.** The requirement of robustness [similar to earthquake] in pier and superstructure to increase the probability for survival.
- **b.** Designed pier and superstructure render the component safe, but absence of robustness leads to reduced probability of survival.
- **c.** Bridges with low pier height are most susceptibility to collapse and failure by toppling of superstructure.
- **d.** High level of deterioration in bridge structure show more susceptibility to collapse.
- **e.** As the rating for Flooding increases, collapse susceptibility is observed even in bridge with lower deteriorated. It is seen that susceptibility varies with height of pier and in zones with high ratings of Flood hazard, the height required to resist over-toppling is above 15 meters.

3. Landslide Susceptibility and Soil Stability

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

a. The requirement of robustness [similar to earthquake] in pier and superstructure to increase the probability for survival.
b. Designed pier and superstructure render the component safe, but absence of robustness leads to reduced probability of survival.
c. Bridges with low pier height are most susceptibility to collapse and failure by toppling of superstructure.
d. High level of deterioration in bridge structure show more susceptibility to collapse.
e. As the rating for Landslide increases, collapse susceptibility is observed even in bridge with lower deteriorated. It is seen that susceptibility varies with height of pier and in zones with high Landslide rating.

4. Cyclone-Induced Structural Stress

High wind speeds and heavy rainfall associated with cyclones can compromise bridge stability. The unseating of superstructures and shear failure due to wind forces are common concerns. The use of robust pier designs, additional anchorage systems, and wind-resistant bearings can enhance a bridge's ability to withstand cyclonic events. Analysis indicate the behavior to be identical to that of Flood impact bridges, probably as Cyclone results in flash flooding due to intense rainfall. The finding are similar to flooding[16].

PROPOSED FRAMEWORK TO ACHIEVE RESILENT SOLUTIONS:

Building resilience in infrastructure requires a multi-dimensional, lifecycle-based approach that goes beyond traditional "repair-and-replace" practices. The proposed framework embeds resilience into planning, design, finance, governance, and community integration, ensuring both risk reduction and long-term socio-economic sustainability.

1. Systems-Based Infrastructure Mapping

Resilience is achieved by understanding how each bridge fits within the larger transport and service network. Mapping evaluates connectivity with highways and logistics corridors, dependency on utilities and emergency services, and the cascading effects of failure. This helps identify critical nodes where failure would cause widespread disruption, guiding targeted investments.

2. Risk-Informed Planning & Anticipatory Design

Instead of reacting to past hazards, planning integrates climate projections, geological risks, and urban growth trends. Bridges are designed for flexibility—using modular or expandable systems—so they remain functional under evolving conditions, making resilience a built-in feature rather than a retrofit.

3. Community-Centric Strategies

Resilient solutions must reflect local needs. Public consultations, social impact assessments, and last-mile connectivity ensure access to essential services. Equity is emphasized so upgrades benefit vulnerable populations, not just well-developed areas. This increases community acceptance and real-world effectiveness.

4. Financial Innovation & Resource Mobilization

Since resilience requires significant investment, the framework encourages diverse financing options: Public-Private Partnerships (PPPs), climate funds, resilience bonds, CSR contributions, and insurance mechanisms. These strategies spread financial risk and highlight resilience as a cost-saving, value-adding investment.

5. Performance-Based Design & Technology Integration

Moving from prescriptive codes to performance-based standards, structures are designed to remain functional during hazards. Use of smart materials, IoT-based monitoring, and low-disruption repair strategies transforms infrastructure into intelligent assets that can adapt and respond in real-time.

6. Institutional Capacity & Governance Reforms

Sustainable resilience requires strong governance. Proposed measures include dedicated resilience cells, professional training, cross-agency coordination, resilience KPIs, and accountability mechanisms. These ensure resilience is integrated into routine decision-making, not treated as an afterthought.

7. Lifecycle Monitoring & Adaptive Maintenance

Resilience is continuous, not one-time. Protocols include real-time structural monitoring, AI-based performance prediction, risk-based inspections, and periodic resilience audits. Feedback loops ensure lessons from past failures are integrated into future designs and policies, keeping infrastructure agile and adaptive.

In summary, the framework represents a shift from reactive to proactive resilience planning. By combining engineering innovations, financial strategies, community participation, and digital intelligence, it creates a sustainable, adaptable, and future-ready infrastructure ecosystem[17].

RESULT FROM GARM:

BRIDGE FAILURE RESULT (For Pier Height=10,12,14,16):

The bridge failure analysis based on different natural hazards reveals varying performance levels of the bridge structure depending on the pier height. The table depicts the impact of earthquakes, flooding, landslides, and cyclones on shear failure of the pier, considering four different pier heights: 10m, 12m, 14m, and 16m.

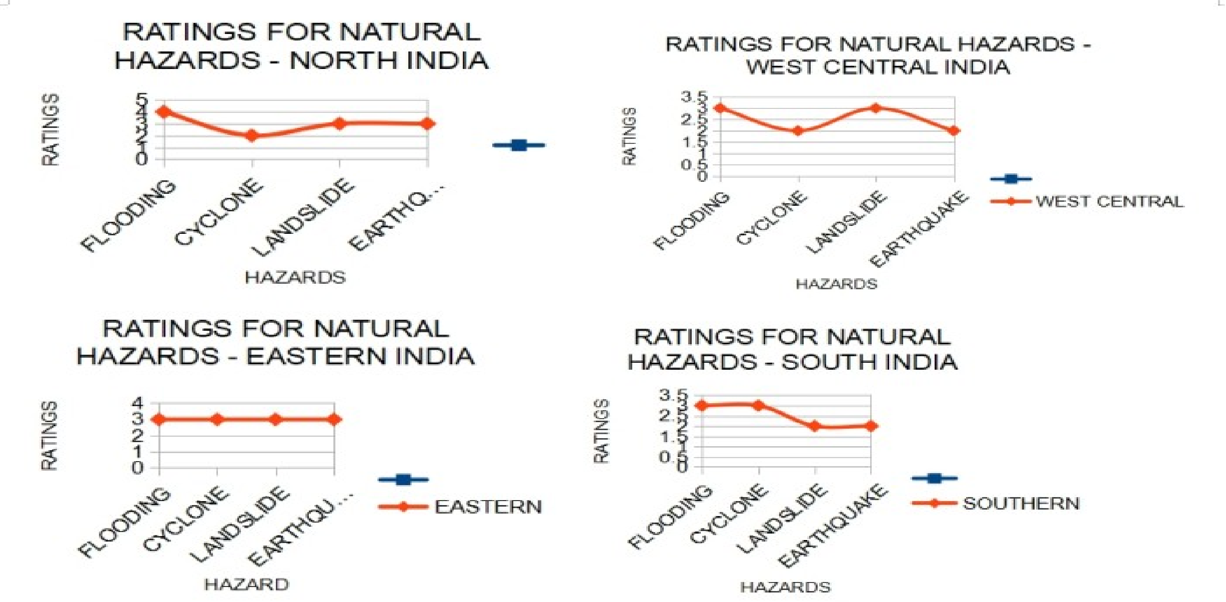
In the case of earthquakes, the bridge shows marginally safe performance at pier heights of 10m, indicating that the structure may withstand the impact but with some minor damages. However, as pier height increases beyond 12m the bridge exhibits high vulnerability to earthquake forces, leading to a probable collapse scenario. This suggests that increasing the height of the pier beyond a certain limit may result in structural instability under earthquake forces. Overall, the bridge performs better at lower heights (10m) but is at greater risk beyond heights (12m) during an earthquake. For flooding scenarios, the analysis shows that the bridge structure is probably safe at pier heights of 10m, at lower flood velocities. However, at a 12m height, the bridge is considered marginally safe, meaning it may suffer some structural damage but will not collapse entirely. As flood increases the velocity and height, the bridge is over topped at a 14m height, and the structure is highly vulnerable, resulting in a probable collapse. But as height of bridge increases beyond 15m, over topping becomes a rare possibility, rendering the bridge to be safe, subject to design limitations. The overall observation suggests that the bridge is more vulnerable to flooding, especially at mid-range pier heights.In landslide conditions, the bridge performance is highly critical. Bridges have to withstand the force of flowing debris at high velocities. At a 10m pier height, the bridge has a high risk of collapse, indicating that it cannot resist the force of sliding soil or rocks. However, at a 12m and 14m height, the bridge structure demonstrates better stability, being rated as probably safe. On the other hand, at a 16m pier height, the performance slightly declines, resulting in a marginally safe condition, where minor structural damage is likely. This analysis reveals that mid-range pier heights are more stable under landslide conditions[18]. For cyclone, the principle reason of collapse is due to flash flooding where the velocity of water flowing is higher and at times the height if water also increases. The analysis shows that the bridge behavior to be similar to that observed during flooding.

Hazard Type	Failure Type	Height = 10	Height = 12	Height = 14	Height = 16
Earthquake	Shear Failure of Pier	Marginally Safe	Probably Collapse	Probably Collapse	Probably Collapse
Flooding	Shear Failure of Pier	Probably Safe	Marginally Safe	Probably Collapse	Probably Safe
Landslide	Shear Failure of Pier	Probably Collapse	Probably Safe	Probably Safe	Marginally Safe
Cyclone	Shear Failure of Pier	Probably Safe	Marginally Safe	Probably Collapse	Probably Safe

GABM RESILIENCE REPORT:

Within Global Analytics for Bridge Management [GABM], Resilience Report presents an in-depth structural and hazard assessment of a typical bridge structure within four main regions— North, Eastern, West Central, and Southern— analyzing their design parameters and vulnerability to various natural hazards. Four bridges with identical geometry but located in different reggions are considered. India has four distinct regions based on the Geo-spatial hazard vulnerability[19]. The four zone defined by their impact are: North India, Eastern India, West Central India, and Southern India.

Typical graphical representation for each regions with respect to their Geo-spatial hazard rating for the selected four hazards are given below.



HAZARD ANALYSIS RESULTS:

The structural safety assessment of four bridges across different hazard types—earthquake, flooding, landslide, and cyclone—indicates varying levels of vulnerability.

For earthquakes, all bridges are generally safe, with Bridge 1 being marginally safe for shear failure of the pier, while others are probably safe.

Flooding poses a significant threat, particularly to Bridge 1, which is at risk of collapse for all failure types, whereas Bridge 2 has marginal safety in some cases, and Bridges 3 and 4 show mixed safety levels.

Landslides do not pose a critical threat, as all bridges are rated probably safe.

Cyclones, however, present a high risk, with Bridge 1 being the most vulnerable, facing probable collapse in all failure scenarios, while the other bridges have marginal to probable safety.

Overall, flooding and cyclones are the most critical hazards, particularly for Bridge 1, while landslides and earthquakes show relatively lower risks. The above results are for bridges with specific geometrical and structural configurations and located in different regions of India. This typically shows the survival probability boundaries.

Hazard Type	Element	Bridge 1 (North)	Bridge 2 (Eastern)	Bridge 3 (West Central)	Bridge 4 (Southern)
Earthquake	Shear Failure of Pier Due to Earthquake	PROBABLY COLLAPSE	PROBABLY SAFE	PROBABLY SAFE	Bridge Probably Safe
	Superstructure Shear Failure Due to Earthquake	PROBABLY COLLAPSE	PROBABLY SAFE	PROBABLY SAFE	Bridge Probably Safe
Flooding	Shear Failure of Pier Due to Flooding	PROBABLY COLLAPSE	PROBABLY COLLAPSE	PROBABLY COLLAPSE	Bridge Probably Safe
	Superstructure Unseating Due to Flooding	PROBABLY COLLAPSE	MARGINALLY SAFE	MARGINALLY SAFE	MARGINALLY SAFE
	Superstructure Shear Failure Due to Flooding	PROBABLY COLLAPSE	MARGINALLY SAFE	PROBABLY SAFE	PROBABLY SAFE
Landslide	Shear Failure of Pier Due to Landslide	PROBABLY SAFE	PROBABLY SAFE	PROBABLY SAFE	PROBABLY SAFE
Cyclone	Shear Failure of Pier Due to Cyclone	PROBABLY COLLAPSE	PROBABLY COLLAPSE	PROBABLY COLLAPSE	MARGINALLY SAFE
	Superstructure Unseating Due to Cyclone	PROBABLY COLLAPSE	MARGINALLY SAFE	MARGINALLY SAFE	PROBABLY SAFE
	Superstructure Shear Failure Due to Cyclone	PROBABLY COLLAPSE	MARGINALLY SAFE	PROBABLY SAFE	PROBABLY SAFE

SUMMARY OF BRIDGE FAILURE ANALYSIS:

Analysis is carried out on bridge with same geometrical and structural configuration but with height of pier [bridge height] varying progressively from 10m to 16 m. Results presented for pier height of 14 and 16 meters. Also the Bridge structural ratings numbers [BSRN] are modified to study the impact of BSRN on bridge survival probability to define the boundaries.

The Bridge Failure Analysis for pier heights of 14m and 16m reveals crucial insights into the structural performance of the bridge under different hazard conditions with varying BSRN. Analysis was conducted on varying heights for BSRN values increasing from 2 progressively to 5 [low distress to very high level of distress]. Variation in ratings of natural hazards indicates the variation of the same bridge in different Geo-spatial regions and the impact of dynamism in natrual hazards due to increasing severity. Study evaluates structural components, including the deck, superstructure, substructure, and scour/foundation, over multiple iterations. The findings highlight the bridge's resilience and vulnerability to earthquakes, flooding, landslides, and cyclones, offering a clear understanding of potential survival boundaries.

- Under earthquake conditions, the bridge is mostly marginally safe (MS) at both 14m and 16m heights, with occasional cases of collapse (C) and safe (S) ratings. This suggests that while the structure can endure moderate seismic activity, as severity increases earthquakes pose a significant risk. So also increasing distress, reduces the boundary of survival.
- In flooding scenarios, the bridge experiences collapse (C) frequently, especially in later iterations, though it remains marginally safe (MS) in some cases. This indicates a high susceptibility to flooding. As height of bridge becomes greater than that of maximum possible flood height the bridge become marginally safe [H=16] for lower distress level.
- The landslide impact reveals the most critical risk, with consistent collapse (C) ratings for both heights, except for a few marginally safe (MS) cases at 16m. This highlights an urgent need for stabilisation measures in landslide-prone areas.
- Under cyclone forces, the bridge is predominantly at risk of collapse (C), particularly at 16m height.

While some instances at 14m height show marginal safety (MS) and safe (S) conditions.

This suggests that aerodynamic improvements and additional wind-resistant design features are necessary to mitigate cyclone-induced failures.

Key Takeaways:

1. Structural degradation over time is evident, with stability ratings declining from 2 to 5 in multiple components.
2. Earthquake performance is relatively moderate, but higher-intensity tremors may lead to collapse.
3. Flooding significantly threatens bridge integrity, with frequent collapse occurrences. Only when the bridges height is above the flood level the survival probabilities increase.
4. Landslides pose the highest risk, with consistent collapse ratings across iterations. The impact of landslides in highest in landslide prone areas with low vegetation cover.
5. Cyclone-induced failures are prominent when it is coupled with high intensity of rain leading to flash floods with very high velocity and high flood height.

The findings emphasize the urgent need for a proactive approach to mitigate risks, particularly against flooding, landslides, and cyclone impacts[19]. While the bridge demonstrates some resilience, proactive maintenance, material enhancements, and hazard-specific design optimizations are critical to improving longevity and safety in high-risk regions.

Hazard Type	Severity Ratings (2-5)	Impact on Bridge
Earthquake	Moderate (2-4)	Ground shaking causes cracks, joint failure, and substructure movement.
Flooding	Severe (3-5)	Leads to scour, displacement, and superstructure unseating.
Landslide	High (3-5)	Causes foundation instability and pier collapse due to movement of soil mass.
Cyclone	Moderate to Severe (3-5)	Results in deck uplift, lateral wind forces, and weakened structural connections coupled with flash flood resulting in higher probabilities of collapse.

DATA AVAILABLE ON GABM		ITERATIONS							
ITERATIONS	**Height of pier**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
BSRN Deck	H = 14, H = 16	5	5	5	4	4	3	3	2
BSRN Super		5	5	5	4	4	3	3	2
BSRN Substructure		5	5	5	4	4	3	3	2
BSRN Scour/ Foundation		5	5	5	4	4	3	3	2
Rating for Earthquake		3	4	5	3	5	3	5	5
Rating for Flooding		3	4	5	3	5	3	5	5
Rating for Landslide		3	4	5	3	5	3	5	5
Rating for Cyclone		3	4	5	3	5	3	5	5
EARTHQUAKE	**H = 14**	MS	MS	C	MS	C	S	MS	MS
	H = 16	MS	MS	C	S	C	S	MS	MS
FLOODING	**H = 14**	MS	C	C	MS	C	S	C	C
	H = 16	MS	C	C	MS	MS	MS	MS	MS
LANDSLIDE	**H = 14**	C	C	C	MS	C	MS	C	C
	H = 16	C	C	C	C	C	C	MS	C
CYCLONE	**H = 14**	MS	C	C	MS	C	S	C	C
	H = 16	MS	C	C	MS	MS	MS	MS	MS

FAILURE MECHANISMS IDENTIFIED

Shear Failure of Piers: Shearing of piers is directly resultant on lateral forces exceeding material strength capacity. The dynamic force of natural hazard like earthquake wave and flooding results in bi-directional force with horizontal component far greater than the vertical component. In cases where the vertical force acts upwards on the bridge, the stability of the bridge is compromised very quickly. Such cases are common during earthquakes, floods, and cyclones. The moderate impact of such forces results in cracking, and tilting. As severity increases collapse results.

Superstructure Unseating: As a consequence of combination of vertical force and horizontal force on superstructure, Bridge deck detaches from supports when the vertical force is an uplift force. Bridge superstructure gets lifted during the vertical uplift surge for a small fraction of the time. During such instances, if the superstructure is subjected to horizontal force due to natural hazard, the bridge superstructure gets unseated from the bearing and tilts, shifting the equilibrium. This results in tilted superstructure in some cases, majorly unseating results in toppling of superstructure. This is common phenomenon caused by earthquakes and flooding. It results in partial or total collapse.

Superstructure Shear Failure: Similar to shearing of pier / substructure, shearing of superstructure also occurs when horizontal force acts on the superstructure which have high restraints. When unseating is avoided due to lateral restraints, the massive horizontal force causes shear effect on the superstructure. Lateral restraints can occur when the uplift forces is not very high, resulting in excessive horizontal stress. Such failure mode is common in floods and seismic events. This results in beam failure and eventual collapse.

Another key failure mode is transition of local substructure or superstructure failure leading to a cascading effect resulting in collapse of the bridge[20]. Such failure or collapse scenario are common in earthquake where local failure in one segment or span of the bridge results in a cascading inpact on adjoining spans causing collapse of the bridge. To showcase resilience-oriented infrastructure planning, seven critical bridges—diverse in location, traffic, condition, and hazard exposure—were selected. This diversity ensured coverage of the varied challenges regional infrastructure faces.

CASE STUDIES:

1. Assessment of Existing Condition:

Each bridge was evaluated per national and international inspection standards, covering structural elements (decks, girders, piers, abutments, bearings, joints, foundations) and signs of deterioration (corrosion, spalling, settlement, fatigue cracks). Serviceability factors such as load capacity, vibration, and user comfort were assessed alongside vulnerability to hazards like floods, earthquakes, cyclones, landslides, and overloading. Historical maintenance data informed understanding of recurring issues and past interventions. This comprehensive evaluation established baseline conditions, estimated remaining service life, and identified urgent needs for repair or retrofitting, forming the basis for resilience-prioritization strategies.

2. Hazard Vulnerability Analysis (HVA):

HVA is essential for understanding how vulnerable bridges are to natural and human-made hazards. In this study, it assessed risks from earthquakes, floods, landslides, and extreme weather. Each bridge was analyzed based on location, hazard history, structural type, and foundation conditions. GIS hazard maps and data from meteorological and seismological agencies were used to evaluate past hazard frequency and intensity. Structural fragility models estimated damage probabilities under different hazard levels.

Specific risk factors, such as foundation scour in flood-prone zones, soil liquefaction in seismic areas, and wind-load exposure, were considered. The analysis also included adaptive capacity (ability to withstand or recover) and redundancy (availability of alternate routes). Results produced a vulnerability index for each bridge, guiding priority setting. High-risk bridges were identified, and targeted measures like seismic retrofitting, flood barriers, or alternate route planning were recommended for resilience improvement.

3. Performance Scoring via MCDM:

To prioritize bridges for resilience enhancement, a Multi-Criteria Decision-Making (MCDM) method was applied. This structured approach evaluates multiple factors simultaneously. Five key criteria were used:

- **Structural Adequacy -** whether the bridge can handle current and future loads.
- **Remaining Service Life -** estimated safe usage period before major intervention.

- **Risk of Failure -** probability of collapse or functional failure under normal or extreme conditions.
- **Socio-Economic Impact -** consequences of bridge disruption on connectivity, economy, and safety.
- **Cost of Rehabilitation -** financial requirements for repair or upgrading.

Each criterion was weighted based on expert input and policy priorities. Bridge scores were normalized for comparability, then aggregated into a composite priority index using a weighted sum model. This index ranked bridges by urgency, helping decision-makers allocate resources transparently. By balancing technical, economic, and social aspects, MCDM ensured that interventions were both resilient and cost-effective.

Cost-Benefit Profiling

Cost-Benefit Profiling served as a decision-support tool to justify investments in resilient bridge infrastructure by weighing both cost implications and long-term benefits. Instead of focusing solely on structural adequacy, the method integrated an economic performance lens to ensure financial sustainability and maximize societal impact.

Cost Components:

a. **Rehabilitation Cost -** This covered all expenses related to restoring bridges to safe operating conditions, including structural repairs, retrofitting of weakened members, strengthening of load-carrying components, and upgrading systems to comply with current design codes and safety standards.

b. **Resilience Enhancement Cost -** This extended beyond conventional repair to include hazard-resistant structural detailing, redundancy in load paths, incorporation of climate adaptation measures (e.g., flood-proofing, seismic design improvements), and integration of monitoring technologies to improve performance and serviceability under extreme events.

Benefit Components:

a. **Direct (Tangible) Benefits** - These included measurable improvements in transport efficiency such as reduced Vehicle Operating Costs (VOC) through smoother pavements, lower fuel consumption, and reduced wear-and-tear on vehicles; decreased Vehicle Operating Time (VOT) due to faster mobility and fewer traffic disruptions; and lower long-term maintenance requirements because of durable, hazard-resilient infrastructure.

b. **Indirect (Intangible) Benefits** - These captured wider socio-economic gains.

c. **Regional Connectivity** - enabling more reliable movement of goods, services, and workforce.

d. **Economic Growth** - improved logistics and market access leading to higher productivity and contribution to local and regional GDP.

e. **Social Equity** - consistent and safe access to essential services such as healthcare, education, and emergency response, particularly for vulnerable and rural communities.

f. **Community Resilience** - reduced disruption during disasters, strengthening public confidence and economic stability.

Decision Integration:

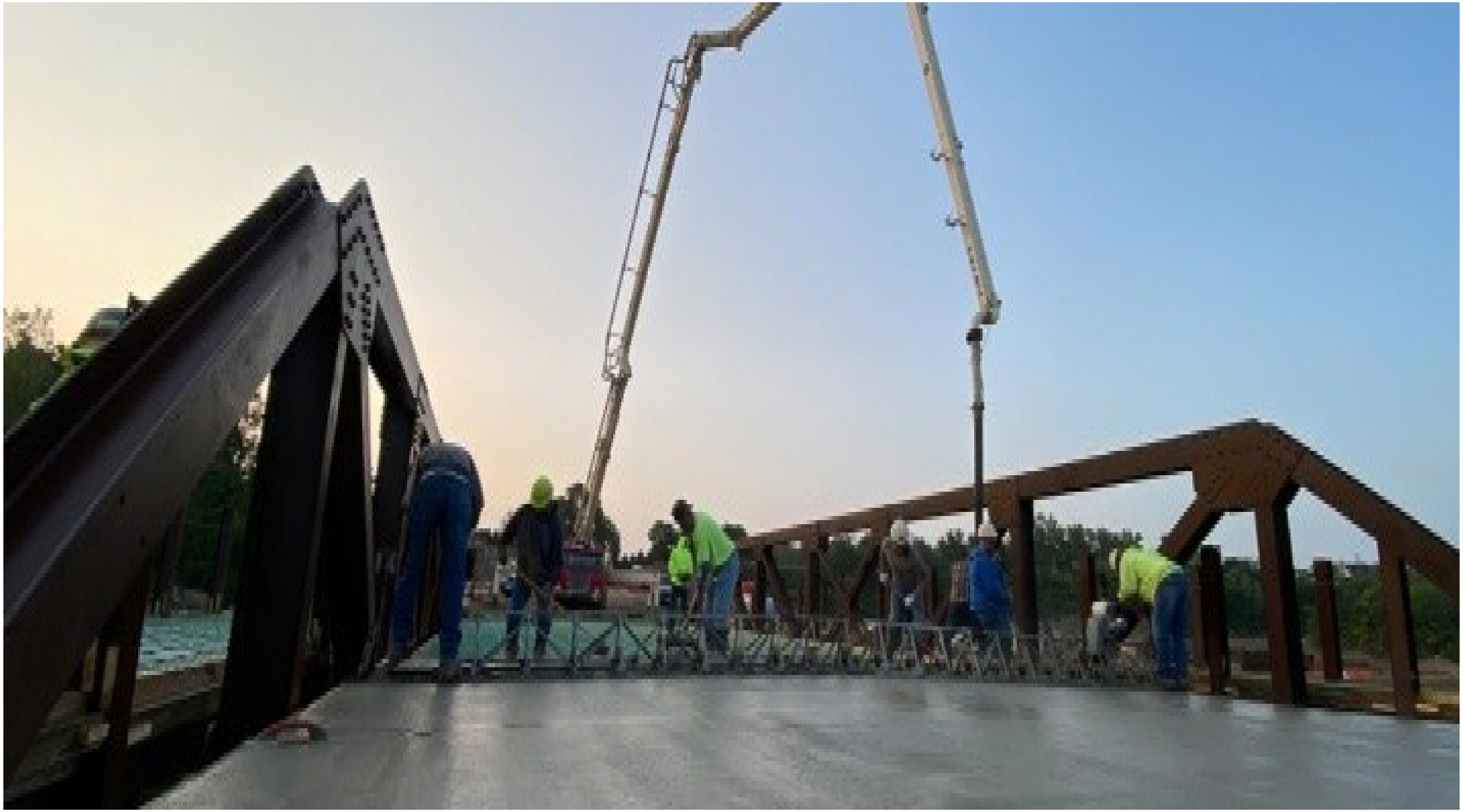
By systematically comparing the total lifecycle costs against the cumulative direct and indirect benefits, the profiling revealed which bridges generated the highest socio-economic return on investment (ROI). This ensured that interventions were not only technically justified but also financially sustainable and socially inclusive, allowing limited resources to be prioritized for projects that maximized both resilience and societal value.

Priority Index Development:

The development of a Priority Index is a key step for identifying which bridges require urgent intervention and which can be scheduled for later action. This index, created using a Multi-Criteria Decision-Making (MCDM) framework, consolidates several technical and socio-economic parameters into a single score. The main factors considered were structural adequacy, remaining service life, risk of failure, rehabilitation cost, and the socio-economic consequences of service disruption.

To ensure fair comparison, data normalization was applied so that different metrics could be evaluated on a common scale. Each criterion was then assigned a weight according to its relative importance—for instance, bridges located on high-traffic corridors or in disaster-prone regions were given higher priority. The weighted scores were aggregated to generate the final Priority Index.

The resulting index provided a ranked list of bridges, categorizing them into immediate attention, medium-term intervention, or routine maintenance. This approach goes beyond structural assessment by also considering community dependence, regional connectivity, and economic impact. As a result, the Priority Index offers policymakers and engineers a systematic, transparent, and proactive tool for allocating limited resources while maximizing resilience and societal value.



RESULTS:

The implementation of the resilience-oriented bridge management framework (GABM–GARM) produced clear evidence of its effectiveness. Seven strategically significant bridges were evaluated using a data-driven approach, combining structural, environmental, economic, and hazard-exposure parameters.

The risk index outputs offered a clear visualization of hazard hotspots, enabling decision-makers to identify where resilience measures would have the greatest impact.

A Priority Index, derived from Multi-Criteria Decision-Making (MCDM) and hazard vulnerability scores, ranked bridges according to resilience needs. Bridges in flood- and earthquake-prone zones showed lower resilience scores, highlighting critical vulnerabilities and the need for urgent intervention.

Financial analysis revealed that while resilience-focused upgrades involve higher upfront costs, they deliver long-term economic benefits—including reduced maintenance expenses, faster recovery after disasters, and minimized socio-economic disruption[21]. Additionally, indirect benefits such as improved regional connectivity, higher productivity, and enhanced social equity strengthened the case for resilience investments.

DISCUSSION

The findings highlight a shift in bridge management, especially for hazard-prone regions. Traditional approaches, often driven by lowest-cost procurement (L1), overlook the cascading impacts of infrastructure failure. By integrating GABM and GARM, this study demonstrates a move from reactive maintenance to proactive resilience planning.

A key insight is the strong correlation between vulnerability scores and socio-economic impacts. Bridges with high traffic, economic corridor connectivity, or strategic importance for emergency logistics showed disproportionately higher indirect losses during hazard events. This emphasizes the need for value-based investment decisions that consider a bridge's broader role in regional stability and growth.

The application of MCDM further strengthened the framework by converting subjective factors—such as community resilience, social vulnerability, and recovery capacity—into quantifiable metrics. Coupled with risk indices, this enabled precise prioritization of interventions and optimized allocation of resources. Ultimately, the approach enhances not only asset durability but also overall societal resilience.

RECOMMENDATIONS

Based on the findings of this study, several strategic measures are proposed to strengthen the integration of resilience into bridge management systems. These recommendations focus on institutional, financial, technical, and collaborative dimensions to ensure that resilience is not an afterthought but a core component of infrastructure planning and maintenance.

1. Institutionalize GABM and GARM

a. Formal Adoption: Government agencies, infrastructure authorities, and bridge management institutions should formally incorporate the Generalized Analytical Bridge Management (GABM) and Generalized Analytical Risk Management (GARM) frameworks into their standard operating procedures (SOPs).
b. Early Integration: Resilience and risk considerations must be introduced from the planning and design stage, instead of being addressed only as reactive measures after a disaster.
c. Policy Frameworks: National and state-level policies should mandate the integration of resilience frameworks, ensuring consistent application across different jurisdictions and agencies.

2. Establish National Benchmarks

a. Standardized Systems: Develop and enforce a uniform resilience and risk scoring system for bridges, leveraging Multi-Criteria Decision-Making (MCDM) tools such as AHP, TOPSIS, or fuzzy logic methods.
b. Transparency & Accountability: Such benchmarks would create objective and transparent evaluation criteria for funding proposals, enabling fair prioritization of projects across states and regions.
c. Data-Driven Decisions: A centralized database of resilience scores, hazard profiles, and performance records should be created, allowing for data-driven decision-making at both micro (individual bridge) and macro (national infrastructure network) levels.

3. *Encourage Resilience Investments*

a. Fiscal Incentives: Introduce financial mechanisms such as resilience bonds, tax rebates, and low-interest loans to encourage investment in resilient infrastructure.

b. Cost-Benefit Perspective: Promote the long-term economic value of resilience by showcasing how higher upfront costs in design and retrofitting are outweighed by reduced repair, rehabilitation, and disaster recovery costs.

c. Public-Private Partnerships (PPP): Engage private stakeholders in resilience-focused projects by ensuring attractive returns and shared risk models, thereby mobilizing additional financing beyond government budgets.

4. *Foster Cross-Sector Collaboration*

a. Multi-Dimensional Coordination: Since resilience spans across engineering, finance, disaster management, and urban development, a multi-sectoral approach is necessary.

b. Joint Task Force: Establish a national or regional task force with representatives from these sectors to ensure that bridge management aligns with wider resilience goals like urban sustainability, climate adaptation, and disaster preparedness.

c. Knowledge Exchange: Create platforms for inter-agency dialogue, research sharing, and collaborative planning, ensuring continuous improvements in resilience strategies.

5. *Build Capacity and Skills*

a. Training Programs: Organize capacity-building initiatives for engineers, bridge inspectors, planners, and policymakers, focusing on resilience assessment methods, GABM/GARM tools, and advanced risk evaluation techniques.

b. Workshops & Simulations: Conduct simulation exercises, workshops, and scenario-based training to help professionals anticipate potential hazard scenarios and evaluate resilience responses.

c. Culture of Risk Awareness: Encourage a risk-informed decision-making culture within institutions, ensuring that professionals are equipped not just with technical knowledge but also with the mindset of resilience-first planning.

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CONCLUSION

Bridges are more than structural entities; they serve as vital lifelines that sustain mobility, economic stability, and emergency responsiveness. Their significance makes their resilience a matter of national and societal priority. However, the challenges posed by aging infrastructure, climate variability, and the rising frequency of natural hazards such as earthquakes, floods, and extreme weather events have exposed critical vulnerabilities. In this context, conventional reactive management approaches, which largely emphasize post-disaster rehabilitation, are proving inadequate. There is a growing necessity to embrace a proactive, resilience-centered strategy for bridge asset management to safeguard safety, functionality, and sustainability over the long term.

The findings of this study highlight that the use of advanced monitoring technologies, predictive analytics, and structural health assessment tools enables timely detection of potential weaknesses. These approaches make preventive interventions possible, reducing the likelihood of sudden failures while extending the service life of bridges. Resilience in this sense is not confined to physical durability alone; it encompasses the ability of bridges to endure both natural and human-induced stresses while ensuring continuity of service. Robust design codes, innovative reinforcement detailing, climate-adaptive material selection, and systematic preventive maintenance emerge as key measures to strengthen both substructures and superstructures against escalating hazard severities.

Central to this vision are the Global Analytics for Bridge Management (GABM) and the Global Analytics for Risk and Resilience Management (GARM) frameworks. Together, they offer a comprehensive methodology for vulnerability assessment, risk modeling, and resilience prioritization. While GABM provides a structured approach to hazard risk assessment, maintenance prioritization, and disaster preparedness, GARM enhances this by integrating Multi-Criteria Decision-Making (MCDM) tools. This ensures that decision-making is not only technically sound but also socio-economically justified, thereby promoting transparency, accountability, and cost-effectiveness[22]. By balancing life-cycle costs against resilience dividends, these frameworks transform infrastructure management into a forward-looking, strategic practice.

The study further emphasizes that bridges designed with robustness, redundancy, and adaptive capacity demonstrate significantly higher survival rates under extreme hazard conditions. Incorporating resilience scoring, hazard vulnerability analysis, and cost-benefit profiling into planning cycles ensures that infrastructure investments are aligned with long-term safety and sustainability objectives. This approach represents a paradigm shift, moving away from reactive, crisis-driven management towards proactive resilience building, which not only safeguards assets but also enhances community preparedness and disaster recovery.

Ultimately, ensuring bridge resilience is both attainable and essential. The adoption of innovative technologies, comprehensive inspection systems, and resilience-based management practices empowers engineers, policymakers, and financial institutions to optimize resources, minimize economic disruptions, and protect lives. As resilience becomes embedded in policy, financing, and engineering practice, bridges will evolve beyond their role as connectors of regions. They will emerge as enablers of national stability, economic prosperity, and sustainable development, ensuring that societies remain safeguarded against the uncertainties of an increasingly hazardous world.

UNDRR DEFINES RESILIENCE AS A CORE NECESSITY:

IT IS NOT A LUXURY BUT A NECESSITY

PROACTIVE INVESTMENTS ARE KEY

" RESILIENCE PAYS"

QUOTES FROM UNDRR:

- NO HAZARD SHOULD BE OVERLOOKED
- EVERY ONE DOLLAR INVESTED IN RESILIENCE SAVES FOUR DOLLARS IN ECONOMIC LOSSES

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