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NAVIGATING TOWARDS RESILIENCE WITHIN BRIDGE MANAGEMENT: NOVEL PERSPECTIVE

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INTRODUCTION

Resilience has not been a factor in Bridge management to date. Resilience gained importance due to the impact of rapid climate change. Resilience, a concept deeply rooted in ecology and psychology, embodies the ability of systems or individuals to endure and recover from adverse conditions. Federal Highways defines resilience, as “Resilience is the ability to **anticipate**, prepare for and **adapt** to changing conditions and **withstand**, **respond** to, and **recover** rapidly from disruptions.” This definition aptly brings into focus the importance of resilience. URG’s research veers on these five critical words namely: Anticipate, Adapt, Withstand, Respond and Recover. Transport networks play a crucial role in the commerce and economic stability of the region.

Resilience of bridges, particularly against natural hazards, ensures and maintains the sustained connectivity/functionality of transportation networks. Resilient bridges are integral to regional stability and economic growth, providing critical links for commerce, emergency response, and daily transportation. A comprehensive approach for ensuring resilient bridges includes innovative designs, sustainable practices, and technological advancements [1,2].

URG made a Voluntary Commitment to Sendai Framework for Voluntary Commitments [SFVC] in 2023 to evolve a “Tool that could identify/ anticipate the response of the ageing, deteriorated bridges to the forces of natural hazards”. Research was needed to enable URG to fulfil the promise to SFVC to develop the required tool.

The research focuses on the “ANTICIPATE” aspects of the definition. Research to identify/ anticipate the response of bridges to natural hazards leads to the resilience of bridges. In the realm of bridge infrastructure, resilience signifies the capacity of physical bridge structural systems to anticipate and absorb shocks, maintain functionality, and swiftly restore to the per-disturbance state.

As societies confront escalating threats from natural disasters, climate change, and ageing infrastructure, the importance of resilience has surged. The aspect of ageing bridges is particularly crucial. The world’s bridge demography indicates over 50% of the bridge population is nearing fifty years of age. Within India, over 45% of bridges are over the age of fifty years. Ageing bridges do have deterioration. Deteriorated bridges face significant risks from earthquakes, floods, cyclones, and landslides; especially when the hazards frequency and severity are dynamically increasing.

Research evolved the required tool to anticipate the response of bridges to natural hazards. These tools are “Global Analytics for Bridge Management [**GABM**]” and Global Analytics for Resilience and Risk Management [**GARM**].

The evolved duo of GABM and GARM integrates proven technologies with risk assessment to facilitate a very comprehensive bridge management system. Such an integrated system contributes significantly to the resilience and sustainability of critical bridge infrastructure. Robust functionality makes GABM / GARM indispensable tools for achieving efficient and effective bridge management along with the critical aspect of risk assessment. The system can accommodate the needs of various network sizes, thus contributing significantly to the resilience and sustainability of critical infrastructure.

The research documentation titled **"Navigating from Deteriorated to Resilient Bridges"** has been submitted to SFVC. The present paper serves as a summary of that extensive submission. This document is available for further study with UNDRR and Sendai Framework for Voluntary Commitments.

OBJECTIVES OF RESEARCH

1. Developing comprehensive tools: **"Global Analytics for Bridge Management" [GABM]** and **Global Analytics for Resilience and Risk Management [GARM].** These tools aim to assess the resilience limits of aging and deteriorated bridges in high-risk zones for natural hazards and evaluating the bridges' ability to withstand such events.
2. Evaluate the effectiveness of Global Analytics for Bridge Management [GABM] and Global Analytics for Resilience and Risk Management [GARM] in enhancing the resilience of ageing bridges against natural hazards. To provide practical insights for integrating resilience into strategic planning and resource allocation for sustainable and safe transportation infrastructure.

RESILIENT BRIDGES IN INFRASTRUCTURE LOGISTICS – KEY CONSIDERATIONS

Bridges are not mere physical structures; they are a vital conduits of connectivity, trade, and regional development. The importance of resilient bridges cannot be overstated. Resilience in bridges has multifaceted significance [3,4]. Bridges play a crucial role in bolstering economic development and ensuring the well-being of communities.

a) Economic Significance of Resilient Bridges

- **Regional Development:** Resilient bridges enable the efficient transportation of goods and people, fostering economic growth and trade. Regions experience increased economic activity, investment, and industrial development.
- **Reduced Disruptions:** Bridges that can withstand and quickly recover from disruptions caused by natural disasters or unforeseen events minimize economic losses and ensure that trade and businesses can continue to operate.

b) Lifelines for Communities

- **Emergency Response:** Resilient bridges play a pivotal role in facilitating emergency response during natural disasters. They are lifelines for first responders, allowing them to reach affected areas swiftly.
- **Daily Commuting:** In everyday life, resilient bridges offer a safety net and act as the backbone of daily commuting for countless individuals.

c) Long-term Durability and Performance

- **Sustainability:** The ability of resilient bridges to endure and recover from adversities reduces the need for frequent repairs and replacements. Such bridges contribute to the long-term sustainability of the region’s growth.

- **Minimized Maintenance Costs:** Designed resilient bridges withstand environmental stressors. When bridges are less prone to damage, there is less need for frequent and expensive maintenance work.

d) Proactive and Adaptive Capability

- **Preparedness and Adaptation:** By focusing on proactive measures, such as developing tools to evaluate how ageing bridges react to natural hazards, we can enhance our capacity to adapt infrastructure in advance of unforeseen events. The ability to ANTICIPATE is the main factor of Resilient bridges.
- **Rapid Recovery and Stability:** Ensuring resilience involves creating systems that rapidly recover from disruptions and return to normal operations. This principle is highlighted in URG's Sendai Framework for Voluntary Commitments to emphasize the development of tools that assist in the swift recovery of bridge infrastructure. By anticipating, the boundaries of probable collapse scenario, response to avoid the scenario designed.

Figure 1: Source Paradigm Shift - Performance Driven Bridge Management, URG

Bridges are essential for efficient movement by enabling crossings over rivers, valleys, and urban landscapes. This efficiency supports robust logistics and supply chains. Additionally, bridges link various regions, foster economic and social integration, and support regional development and equitable resource distribution. By providing access to otherwise isolated areas, bridges facilitate tourism, trade, and the provision of essential services to rural and under-served communities.

Bridge resilience ensures that emergency services can operate effectively, minimizing the impact of disasters on communities and economies. Bridges are vital for national security, supporting the strategic mobility of military forces and contributing to the overall stability and security of the nation. URG's Sendai Framework for Voluntary Commitments highlights the importance of anticipating and mitigating the impacts of natural hazards on ageing and deteriorating bridges through proactive measures and community collaboration.

INCREASING IMPACT OF NATURAL HAZARDS ON BRIDGES

Of the Natural hazards that affect Bridge structures, the hazards that cause the maximum impact are earthquakes, floods, cyclones, and landslides. These four hazards together or singularly pose significant threats to bridge infrastructure, leading at times to catastrophic failures that disrupt transportation networks and endanger lives. Understanding their impact is crucial for developing resilient bridge designs and effective management strategies [5,6].

Stated below are the key points relating to the impact of these hazards on bridges:

a) Common Failure Mechanisms:

- ➢ Substructure and Foundation Failures: Due to shear/ horizontal forces, the substructure and foundations are vulnerable to failure, often compromising the bridge's stability. Scouring and shearing of substructure are at times the starting point for cascading failure scenarios.
- ➢ Superstructure Failures: Horizontal forces can lead to the unseating or toppling of superstructure elements, significantly endangering the bridge's integrity.

b) Cascading Impacts:

- ➢ The failure mechanisms mentioned above can trigger cascading effects, leading to the collapse of adjoining bridge elements and the entire span, resulting in loss of connectivity and service.

c) Strength Reduction resulting from Deterioration:

- ➢ Historical evidence confirms this critical fact. Previous inspection data help identify the reduction in strength of concrete and rebars. Analyses anticipate the response of bridge structure based on these reduction factors. Standard design equations, adjusted with reduction factors for deteriorated materials, are used to categorize bridges based on their safety status.

d) **Evaluation and Resilience Planning:**

- ➢ The study evaluates the bridge's response to varying levels of natural hazards, defining survival boundaries based on deterioration levels. This helps in enhancing resilience planning, although current limitations due to diverse design and construction methods offer opportunities to extend research to other bridge forms.

EVALUATING BRIDGE FAILURE SCENARIOS

Evaluating bridge failure scenarios involves a thorough assessment of potential failure modes under natural hazards [7,8]. This approach integrates advanced analytical techniques to anticipate and mitigate risks; ensuring bridges remain resilient against extreme conditions.

The four natural hazards are the major hazards that have caused the maximum number of bridge collapses. The most common failure mechanism is:

- ➢ Failure of substructure and foundations due to shear force;
- ➢ Failures in superstructure due to horizontal force resulting in unseating of the superstructure;
- ➢ Failures in superstructure due to horizontal force resulting in toppling of the superstructure elements.

All the above-mentioned failure mechanisms have the potential to result in a cascading impact on adjoining elements. Such cascading causes the failure of the entire span. Each of the four hazards [Earthquake, Flooding, Cyclone, and Landslides] have the potential to cause either one of the above-mentioned failures or multiple failures. Horizontal force is the most conspicuous of the forces that influence the bridge response.

Research focuses on the above three scenarios. Evaluation of the deterioration model and severity definition as derived from Bridge management determines the deterioration level in the bridge. The incremental severity of distress yielded a reduction in strength. Both concrete and rebars exhibit a reduction in strength capacity.

Standard strength capacity equations of bridge design procedures with reduction factors yield response of the bridge elements. Such analysis establishes the probability of bridge categorization as either Safe, Marginally Safe or otherwise stated as having a higher probability of Collapse.

Such analysis also enables one to evaluate the response of deteriorated bridges to varying severity of natural hazards. The analysis defines the boundaries of the bridge survival for the inspected levels of deterioration/distress. Evaluated boundaries are significant for understanding the approach to be adopted to enhance resilience planning.

Present limitations of this approach arise due to varied design and construction methods used in today's bridges. This limitation gives an opportunity to further the research scope to cover other types of bridges.

Data Utilization and Testing

Historical data from past bridge inspections and tests over fifteen years helps assess stress reductions for older bridges, while core testing and ultra-pulse velocity results determine strength capacity reductions linked to distress. Rating numbers from bridge management projects further refine failure analysis by indicating distress levels and defining reduction factors.

Testing and Results

Beta testing revealed that bridges over 50% of their Design Service Life [DSL] age; with BSRN values above 3.5, have a high collapse probability under severe natural hazard ratings. The global bridge population distribution shows that 40-50% of bridges are ageing, highlighting the need for enhanced resilience and a shift from mono-criterion to multi-criteria decision-making for effective fund management. The methodology for evaluating bridge failure scenarios involves a detailed assessment of potential failure modes under natural hazards, utilizing advanced analytical techniques to enhance resilience.

Extensive analysis of data on bridges during Beta Testing enables URG to define the key findings of using the Resilience module of GABM/GARM. Ten bridge dimensions from the Maharashtra state of India were utilized to determine the response of that bridge to varying intensity of natural hazards [All four hazards acting singularly]. The main findings listed below shed light on the various boundaries of resilience that the bridges exhibit.

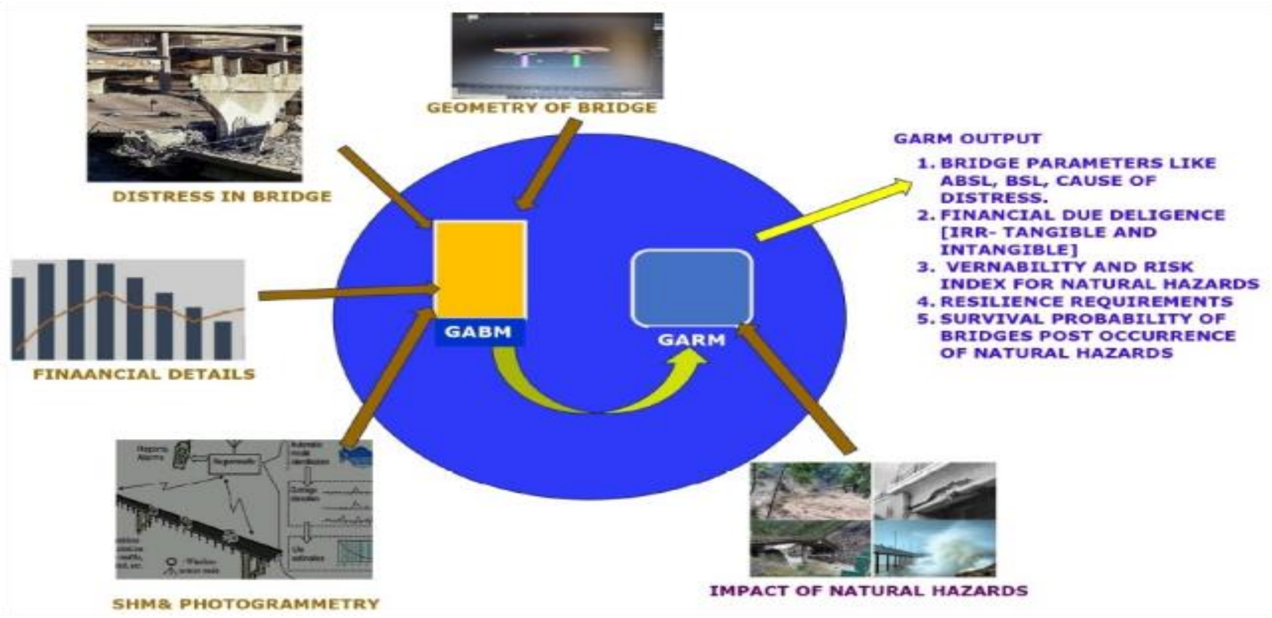


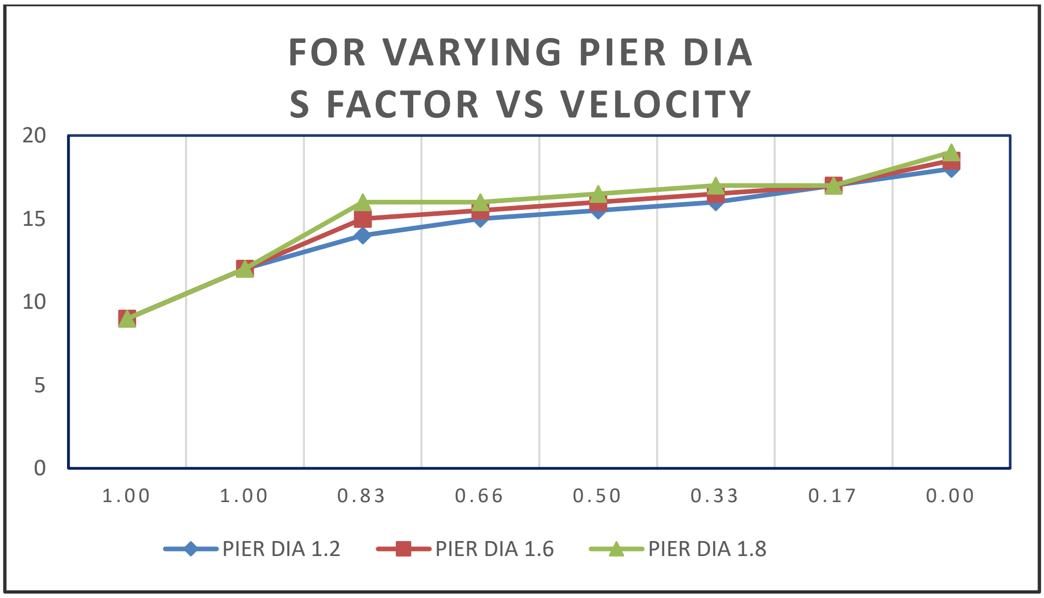
Figure 2: GABM and GARM integrated Duo Source UBMS literature

MAIN FINDINGS FROM GABM'S RESILIENCE MODULE

1. The principal cause leading to the failure of bridge components due to the four natural hazards arises from the shear failure of the substructure, unseating and overturning/toppling of superstructure components. One element failure shows the possibility of a cascading effect leading to at times the entire bridge failure.
2. All three failure modes result from horizontal force acting on the bridge structure.
3. During floods (due to heavy rain upstream or cyclone) and/or debris flowing post landslides, the origin of the first possible failure arises from scouring and shear failure of the substructure. The high velocity of flowing water causes scouring resulting in very high horizontal force on the substructure.
4. If all other geometrical parameters of the bridge structure are the same, the substructure will result in failure under two clear boundaries namely: BSRN value greater than 3.5, and water flow velocity exceeding 20 kmph.
5. The progressive failure transgression occurs [for same BSRN] as velocity exceeds 15 kmph, the substructure will show signs of moving from being Safe to Marginally Safe. This transgression progresses through all three modes of failure mechanisms when the velocity exceeds 20 to 22 km/h.
6. The above-stated velocity causing failure is for bridges with a minimum dimension of circular substructure elements to be over 1.75 m. If this dimension reduces to 1.20 m, the velocity of 16 kmph is sufficient to cause failure.
7. Rectangular substructure and deeper superstructure show reduced probability of collapse. Velocity exceeding 25 kmph can cause failure in bridges with Rectangular substructure and girder depth over 2.25 m.
8. Increasing the minimum dimensions of the substructure with shear reinforcements of higher diameter will result in enhanced resilience during floods, which do not overtop the bridge deck.

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

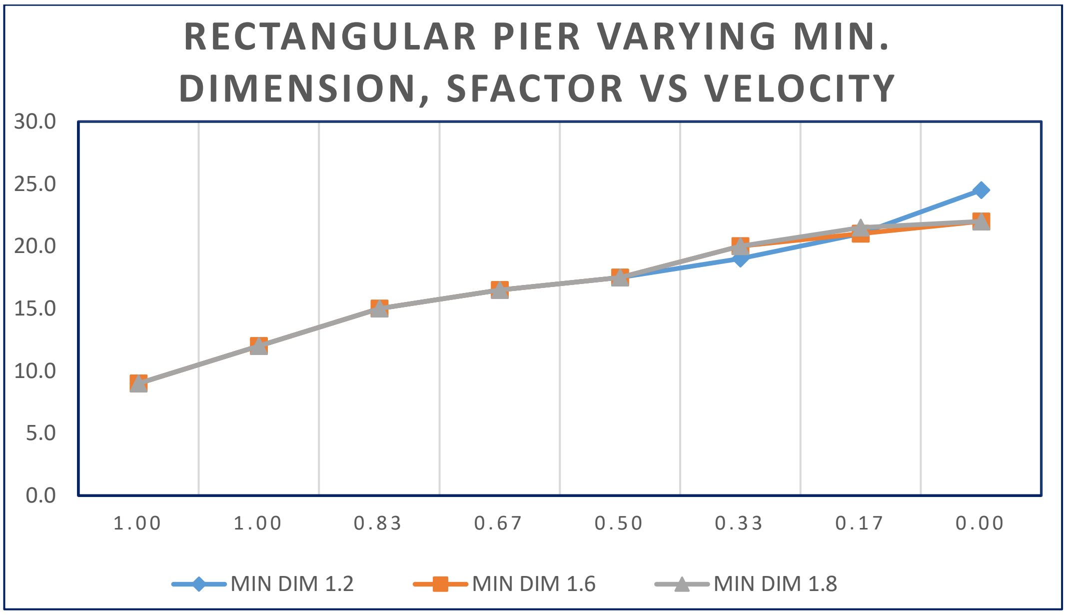


Graph 1: From All Safe to All Collapse as velocity increases [Circular Piers]

The response of a rectangular pier with a minimum dimension varying from 1.2 m to 1.8 m was evaluated and the velocity was found to be greater for such sections as compared to a circular pier.

	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

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

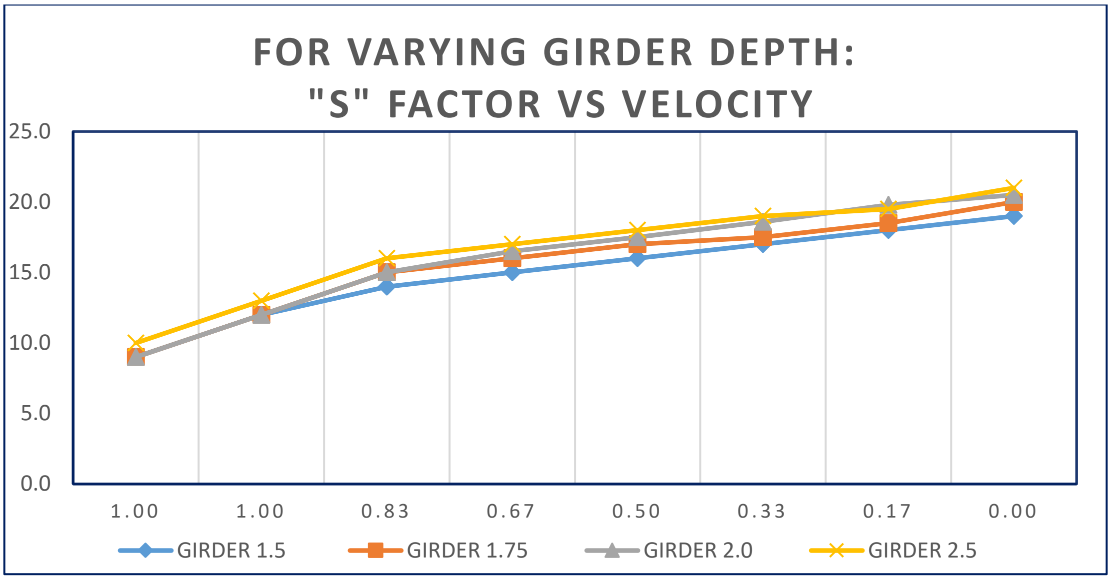


Graph 2: From All Safe to All Collapse as velocity increases [Rectangular Piers]

A similar analysis was conducted for variation in the geometrical dimensions of the superstructure [Girder] by modifying the girder depth from 1.5 m to 2.5 m. The velocity at which collapse first occurs ranges between 17 to 19 kmph.

	Girder with depth varying from min dimension 1.5 to 2.5 meters. Width same at 0.75 M, Concrete M40 and shear rebar 18mm at 150 mm C/C							
GIRDE DEPTH	**Velocity of water flow**							
1.5	9.0	12.0	14.0	15.0	16.0	17.0	18.0	19.0
1.75	9.0	12.0	15.0	16.0	17.0	17.5	18.5	20.0
2	9	12	15	16.5	17.5	18.6	19.8	20.5
2.5	10	13	16	17	18	19	19.5	21
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

Table 3: From All Safe to All Collapse as velocity increases [Girders]



Graph 3: From All Safe to All Collapse as velocity increases [Girders]

In all the above examples, one geometrical parameter is changed and the boundary of resilience is evaluated. The response of a deteriorated bridge with an Average BSRN above 3.5 (indicating an overall reduction in strength to the tune of 40%) and with a natural hazard rating above 3.5 resulting in the velocity of flowing water/landslide debris increasing from 9 kmph to failure is evaluated. The SAFETY FACTOR or “S” factor vs increasing velocity is plotted. The “S” factor of “1” indicates that for all types of failures, the bridge is probably SAFE. The “S” factor of zero indicates a scenario wherein for all three failure modes the bridge probably will collapse.

1. The superstructure overturning or unseating can be avoided by better support conditions and providing cross bracing. The increased gross weight of the bridge also helps in enhanced resilience.
2. Earthquakes exceeding 6.6 on the Richter scale will result in an identical response from the bridge.
3. For the bridge to be resilient under extreme force of natural hazards the bridge geometry will need to be robust and the deterioration level will need to be low. For the same geometry, the bridge with low deterioration and low strength reduction is probably safe for the velocity of flow below 23 kmph/earthquake below 7 on the Richter scale.

Figure 3: Short term objectives of GABM & GARM   Source: UBMS literature

Figure 4: Long-term objectives of GABM & GARM Source UBMS literature

CONCLUSION

The research provides a critical examination of the resilience of reinforced concrete bridges, highlighting the urgent need for enhanced strategies to address ageing infrastructure. The study focused on bridges with simple geometries and found that deterioration significantly increases the likelihood of collapse under severe natural hazards, emphasizing the necessity for targeted resilience enhancements.

Key findings reveal that flood velocity, water height, and earthquake forces are crucial factors affecting bridge survival, highlighting the importance of understanding these dynamics to improve bridge design and management. The research also points out the limitations of existing mono-criterion approaches in bridge management and advocates for a transition to multi-criteria decision-making processes to address the complexities of resilience effectively.

The study has led to the development of two essential tools, GABM and GARM, which offer deeper insights into risk assessment and remedial interventions for ageing bridges. It emphasizes the need for a proactive approach to bridge management, integrating risk assessment and resilience planning to prevent bridges from becoming liabilities during natural disasters. Furthermore, the research highlights the growing impact of climate change and the inadequacy of traditional design standards in predicting and mitigating risks.

The research scope was limited to simple reinforced concrete bridges, two to four-lane bridges, lengths up to 250 m, width of four lanes, height restricted to 8 m from normal water level, with multiple spans. Complicated design geometry like cable stay, pre-stressed girders, and arched geometry have not been used during the research.

The key findings of the research indicate that ageing bridges that exhibit deterioration are bound to collapse when the severity of natural hazards increases. Increasing degrees of deterioration lowered the survival probability of the bridge.

By defining the various boundaries for the bridge structure to survive, our research helps to provide solutions to enhance resilience. Thus, our research highlights the key factors that, if adopted, can enhance resilience in bridge structure.

URG's research also indicates the limits of severity that the bridge geometry is able to survive. The velocity of flowing water during floods and the height of flooding are two critical factors that can determine which of the bridges will survive. Flash floods and floods with debris increased the probability of collapse for similar bridges. Similarly, the horizontal force due to earthquakes decides the fate of the bridge.

The findings advocate for increased investment in resilience strategies, advanced monitoring systems, and community engagement to ensure bridges remain functional and safe. These measures are crucial not only for immediate safety but also for long-term economic stability and disaster risk reduction. Ultimately, the research emphasizes the vital role of resilient infrastructure in maintaining connectivity, supporting economic activities, and enhancing regional stability in the face of escalating natural hazards.

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