BILINGUAL PUBLISHING GROUP

Journal of Architectural Environment & Structural Engineering Research
https://journals.bilpubgroup.com/index.php/jaeser

ARTICLE

Sustainability of Bridges: Risk Mitigation for Natural Hazards

Sachidanand Joshi [*], ***Atharvi Thorat, Harshali Dehadray, Mayuri Tundalwar***

UBMS Research Group, Mumbai, 400062, India

ABSTRACT

Bridges serve as essential parts of transportation infrastructure, facilitating the movement of people and goods across rivers, valleys, and other obstacles. However, they are also susceptible to a wide range of natural hazards, including floods, earthquakes, and landslides, which can damage or even collapse these structures, leading to severe economic and human losses. A risk index has been developed to address this issue, which quantifies the likelihood and severity of natural hazards occurring in a specific location. The application of risk indices for natural hazards in bridge management involves a data collection process and mathematical modelling. The data collection process gathers information on bridges' location, condition, and vulnerability, while mathematical modelling uses the data to assess the risk of natural hazards. Overall, risk indices provide a quantitative measure of the vulnerability of bridges to natural hazards and help to prioritize maintenance and repair activities. Mitigation measures are then evaluated and implemented based on the risk assessment results. By using this tool, the UBMS research group has developed an algorithm for risk assessment which will be essential in the decision-making process, specifically focused on enhancing Fund Optimization, Deterioration Modelling, and Risk Analysis. These developments effectively fulfill the primary objectives associated with addressing and mitigating hazards. This development also helps bridge managers understand the potential threats posed by natural hazards and allocate resources more efficiently to ensure the safety and longevity of critical transportation infrastructure.

Keywords: Hazards; Risk index; Vulnerability; Mitigation measures; Decision-making process; Fund optimization; Deterioration modelling; Risk analysis

*CORRESPONDING AUTHOR:
Sachidanand Joshi, UBMS Research Group, Mumbai, 400062, India; Email: sachidanand@ubmsresearchgroup.com

ARTICLE INFO
Received: 19 June 2023 | Revised: 28 July 2023 | Accepted: 4 August 2023 | Published Online: 15 August 2023
DOI: https://doi.org/10.30564/jaeser.v6i3.5807

CITATION
Joshi, S., Thorat, A., Dehadray, H., et al., 2023. Sustainability of Bridges: Risk Mitigation for Natural Hazards. Journal of Architectural Environment & Structural Engineering Research. 6(3): 4-16. DOI: https://doi.org/10.30564/jaeser.v6i3.5807

1. Introduction

The paper aims to highlight the urgency and importance of including risk assessment rising from natural hazards within bridge management to render the bridges to be resilient to these natural hazards. The focus of the research has been on earthquakes, floods, cyclones, and landslides, which can have devastating effects on human life and infrastructure.

In recent times vagaries of climate change have impacted the world over. In India too, the entire north India experienced significant devastation from floods, where this year more than 100 people lost their lives and scores were injured as of mid-July, 2023. The floods caused extensive damage to infrastructure, leading to thousands of blocked roads and disruptions in power supply. Around 70,000 tourists were evacuated with the help of the Indian Army and the National Disaster Response Force. Many cities were also severely affected, with roads washed away, leaving residents and tourists stranded. Rural areas also faced the consequences of incessant rains, resulting in waterlogged roads, submerged cars, and flooded fields in large parts of Punjab, Himachal Pradesh.

Many places around the world are witnessing single-day extreme situations like the highest rainfall/snowfall in over five to six decades, very high temperatures, and extreme cyclonic weather/hurricanes and other extremes. Such extremes are witnessed in all corners of the world including Europe, America, Asia, and Australia. Cyclones affect the vast Indian coast frequently and the recent spate of occurrences along both the east and west coasts have resulted in NDMA officials focusing on cyclones. Earthquakes have impacted scores of bridges in the past. Like cyclones, floods, and landslides impact of earthquakes also needs to be addressed in India. The entire Himalayan region is prone to sporadic earthquakes.

These sudden and frequent extremities of weather around the world and in India highlight the pressing need for improved disaster management and mitigation measures in the region. In recent years, the frequency and severity of natural disasters have notably increased, largely attributed to factors like climate change and rapid urbanization [1]. Bridges, as critical infrastructure, play a vital role in facilitating the movement of people and goods [2]. However, their susceptibility to natural hazards demands special attention to ensure the safety and functionality of transportation networks. Most Bridge Management systems [BMS] do not comprehensively address the issue of risk arising from natural occurrences in a proactive manner. It is only when distress is observed that BMS comes up with remedial interventions.

To effectively manage natural hazards and mitigate their impact on bridges, a proactive approach is essential. This approach involves identifying vulnerable areas and implementing appropriate mitigation measures. A promising tool that aids in this process is the Risk Index for hazards [3]. The risk index quantifies the probability and severity of a natural hazard occurring in a specific location. It considers factors such as the likelihood of the hazard occurring, the intensity of the hazard, and the vulnerability of the population and infrastructure in the area [4]. The risk index proves valuable in identifying the most vulnerable areas, prioritizing mitigation measures, and evaluating the effectiveness of emergency response plans.

As a result, the development of risk indices for hazards has become a critical component of hazard research and management. These risk indices have found applications in assessing various natural hazards, including earthquakes, floods, cyclones, and landslides [5].

This paper aims to review the utilization of risk indices for natural hazards within the context of the Global Analytics for Bridge Management [GABM] application. Specifically, the paper focuses on the methodology and application of risk indices for natural hazards in bridge management. Considering the vulnerability of bridges to catastrophic events, this study aims to provide a viable method for data collection related to hazards, mathematical modelling of incorporating risk index within decision-making tool of fund optimization in BMS and providing a proactive scenario for implementing mitigation measures with the incorporation of risk indices in bridge management.

The primary objective is to explore how the utilization of risk indices can enhance the resilience of bridge infrastructure and ensure the safety of the travelling public. This research contributes to building possibly robust transportation networks that can withstand the increasing challenges posed by natural hazards.

1.1 Challenging scenario for bridge management

In today's scenario, climate changes have resulted in creating uncertainty in the way nature behaves. Natural hazards have become more unpredictable, more intense, and more frequent. Achieving or maintaining the sustainability of bridge structures under these circumstances is challenging but essential.

Bridges serve as essential parts of transportation infrastructure, facilitating the movement of people and goods across rivers, valleys, and other obstacles. However, they are also susceptible to floods, earthquakes, landslides, and other similar natural hazards. The impact of natural hazards is not predictable, and sudden and can damage these bridge structures at times leading to the failure of bridges. Such impact cause severe economic and human losses. To address this issue, a proper mitigation or containment protocol is essential. Conventional Bridge Management did address this issue in a limited way [6]. The response of the bridge to the hazard depends on the bridge's design, construction, geology, location, age, and other factors. These factors also need to be accounted for.

The application of risk indices for natural hazards in Bridge Management involves mathematical modelling applied to the data collected, regarding the occurrence of natural hazards, their intensity and frequency. The data collection process gathers information on bridges' location, condition, and vulnerability. Subsequently, mathematical modelling is applied to this data to assess the risk of natural hazards. Evaluation of risk index and vulnerability also enables adaptation of preventive proactive structural strengthening of the bridge structure. Mitigation measures are then evaluated and implemented based on the risk assessment results.

By using this tool within the algorithm for risk assessment, it is possible to contain the possibility of damage and achieve mitigation in a limited way. Proactive usage of the module in the decision-making process is recommended.

1.2 Past and present research

Risk mitigation for natural hazards in bridge management has been researched for a long. One study discusses supporting the life cycle management of bridges through multi-hazard reliability and risk assessment [7]. The study utilizes metamodels as an efficient strategy for developing parameterized time-dependent bridge fragilities for multiple hazards. Threats considered in the case studies include earthquakes, hurricanes, ageing and deterioration, and live loads.

Swagata Banerjee et al. (2013) proposed a highway transportation network composed of many bridges that share the same statistical structural attributes and configurations as the example bridges, which can utilize fragility curves and risk curves to portray the vulnerability and associated risk of these highway bridges to regional multi-hazard events [8].

Paul D. Thompson et al. (2016) explore the concept of risk in the context of transportation facilities, with a particular focus on bridges. Adverse events can be caused by natural hazards such as earthquakes, floods, and wildfires, as well as man-made hazards like overloads and collisions. The Moving Ahead for Progress in the 21st Century Act (MAP-21) emphasizes risk-based asset management without specifying risk performance measures but outlines national performance goals related to safety, infrastructure condition, congestion reduction, and more. Adverse events can affect these national goals, and various tools like accident analysis and life cycle cost analysis can help estimate the consequences of such events. AASHTOWare Bridge Management software (BrM), offers multi-objective performance frameworks to aid in project evaluation and resource allocation. The literature review also highlights the need for improved guidance on engineering risk assessment, post-event evaluation, and rapid recovery strategies for infrastructure assets [7].

The review of past research, provided an extensive overview of the utilization of risk indices for natural hazards, emphasizing the importance of such tools in civil engineering and hazard management. The review highlighted the challenges faced in bridge management due to the increasing unpredictability and intensity of natural hazards. It also described how risk indices are essential in assessing vulnerability, prioritizing resources, and evaluating mitigation measures.

The ground realities in India and the review identified four major natural hazards relevant to bridge management: earthquakes, floods, cyclones, and landslides. Each hazard requires a specific risk index tailored to its characteristics. The review emphasized the need for data integration, hazard mapping, and comprehensive risk assessment to create effective risk indices.

Application of risk indices in bridge management:

Earthquake Risk Indices: These indices consider seismic hazard assessments, structural vulnerability, and potential consequences such as economic impact and life loss. By quantifying the risk, bridge managers can prioritize retrofitting measures and emergency response plans [9].

Landslide Risk Indices: Risk indices for landslides assess bridge structures' susceptibility to potential damage caused by geological events. These studies analyze geological and geotechnical data to identify landslide-prone areas and evaluate bridges' vulnerability in such regions [4].

Cyclone Risk Indices: Risk assessment models for wind-induced vibrations and fatigue damage in long-span and cable-stayed bridges have been developed. These models consider factors such as wind speed, bridge geometry, and structural characteristics to assess bridge vulnerability to high winds [5].

Flood Risk Indices: Risk indices for flood hazards consider factors like flood frequency, intensity, bridge location, and population vulnerability. These indices identify flood-prone areas, optimize mitigation measures, and assess emergency response plans [7].

The literature review underscores the vital role of risk indices in bridge management, as they assess vulnerability, optimize resource allocation, and implement effective mitigation measures for natural hazards like earthquakes, floods, and landslides. The integration of risk indices within the Global Analytics for Bridge Management (GABM) presented, showcases its capability to rank bridges based on their risk levels, facilitating the identification of priority structures in need of immediate attention and targeted interventions. Furthermore, it enables scenario analysis, allowing bridge managers to assess the effectiveness of various mitigation strategies and make informed decisions. It embodies a proactive and data-driven approach, ensuring the safety, sustainability, and resilience of bridge infrastructure, and enabling effective decision-making to safeguard critical transportation infrastructure [10].

2. Risk assessment methodology for natural hazards

Natural hazards such as earthquakes, floods, hurricanes, and landslides can have devastating effects on human life and property. The frequency and severity of natural disasters have increased significantly in recent years due to factors such as climate change and urbanization. The management of natural hazards requires a proactive approach that involves the identification of vulnerable areas and the implementation of mitigation measures by proactively strengthening the bridges which are more susceptible to damage. Bridges are important infrastructure links. Their vulnerability is very high and needs special attention. The Bridge Management system needs to incorporate a module for such risk assessment and analysis. Based on the analysis, the proper action is required for the mitigation of the evaluated risks.

The sustainability of bridges and the effective mitigation of risks associated with natural hazards necessitate a systematic and multidisciplinary approach. This research employs a methodology that encompasses several key components. A thorough examination of deterioration mechanisms and their interaction with natural hazards is conducted. This involves studying the effects of various environmental factors such as temperature fluctuations, moisture, and chemical exposure on bridge materials and structural integrity. By understanding these deterioration processes, suitable preventive and maintenance measures can be identified. The risk assessment also involves considering the consequences of bridge failure, including the impact on transportation networks, economic losses, and potential harm to human life.

The process essentially begins with the collection of historical data and an understanding of the geography of the area surrounding the bridge. This requires the user of GABM to collate the historical event and during the past few years for frequently occurring events. Four major natural hazards are in focus for India. They are earthquakes, floods, cyclones, and landslides. Earthquakes and floods are more predominant in the northern fringes of India abutting the Himalayan ranges extending from Kashmir to Assam. Cyclones are more predominant in the coastal belt of India which is over 15,000 km long. Landslides are in focus in the foothills of all mountain ranges. Over 60% of India is hazard-prone and hence the effort to mitigate the impact. Two types of values are evaluated from this data; namely the frequency of occurrences based on long-term data and the uncertainty coefficient based on the increased frequency over the last few years. Data are also collected regarding the intensity of past events.

The extent of damage that occurred during past events defines the possibility of damage that can occur if No action is taken to mitigate the same. Here an important factor that is accounted for is the propagation of distress in the bridge structure due to the event. Many times, the frequent occurrence of the event leads to a progression of distress that can culminate in a collapse during the future occurrence. Such progression is evaluated and steps to mitigate this progression are also accounted for.

Consequences refer to the impact of the event on the bridge if it were to occur. This includes the potential damage to the bridge, disruption to transportation networks, and potential loss of life or injuries. Consequences can vary based on the specific characteristics of the bridge, such as its structural design, materials used, and traffic volume [11]. The total cost of retrofit is evaluated and termed as consequence cost. This consequence cost is not just the cost of rehabilitation and restoration of the level of service but includes the cost arising from loss of service. GABM has within the database values assigned to the Socio-Economic impact of the bridge on the region of influence. These Socio-Economic parameters enable evaluation of the cost of disruptions arising from future occurrences.

The establishment of a risk index for hazards entails the use of mathematical models to quantify the likelihood and severity of a hazard occurring in a specific location. The risk index is used to assess the potential risks associated with bridges. This index combines information on the likelihood of a risk event occurring and the consequences of that event. By considering both factors, bridge managers can prioritize their resources and take appropriate actions to mitigate risks effectively. Likelihood refers to the probability or frequency of a risk event occurring. It considers various factors such as the condition of the bridge, environmental factors, and usage patterns. For example, a bridge located in an area prone to earthquakes would have a higher likelihood of experiencing a seismic event compared to a bridge located in a seismically stable region.

To develop a risk index, bridge managers typically need to assign numerical values or ratings to both the likelihood and consequences of various risk events. These ratings can be based on historical data, expert opinions, or analytical models. For example, likelihood ratings can be categorized as low, medium, or high, while consequence ratings can be classified as minor, moderate, or severe. Once the likelihood and consequence ratings are assigned, they are combined in a predetermined manner to calculate the risk index for each natural hazard. The formula can be as simple as multiplying the likelihood and consequence ratings together, or it can involve more complex mathematical or statistical models. The resulting risk index provides a quantitative measure of the overall risk level associated with each hazard type.

The risk index, presently is based on a simple combination of likelihood and consequences to provide a systematic approach to identifying, assessing, and prioritizing risks associated with bridges. GABM allows user to use their discretion to modify risk index calculated values to values that are based on their judgement or past historical experience. Based on usage, the refinements in the evaluation of the risk index are inbuilt using an AI tool that captures the evaluated values and compares them with accepted values. Refinement in the evaluation process is statistically AI-driven. Using the application over a period in a particular region will yield a more refined and stable evaluation process. By utilizing this index, bridge managers can make informed decisions and take proactive steps to ensure the safety and longevity of bridge infrastructure.

Following are the steps for calculating Risk Indices.

2.1 Gather historical data

- Collect detailed information about the bridge's design, construction, maintenance history, and materials used (**Figures 1B and 1C**).
- Gather data on environmental conditions such as weather patterns, seismic activity, flood risks, and soil characteristics.

2.2 Identify hazards

- Identify and categorize potential hazards that could affect the bridge (e.g., earthquakes, floods, landslides, and cyclones) (**Figure 1A**).

2.3 Assess vulnerability

- Evaluate the bridge's vulnerability to each identified hazard by using.
  a. Likelihood of service disruption.
  b. Likelihood of occurrence of the extreme event of a given magnitude that is specified by the hazard scenario, estimated for the bridge.
  c. Consequence of service disruption.
  d. Weight Factors: Assign relative weights to the different hazard categories and safety based on their importance and potential impact. Weighting factors may vary based on the specific objectives of the risk index.
  e. This leads to calculating:
  i. Lebh (Likelihood of event happening).
  ii. Ldbh (Likelihood of event happening in the bridge's lifetime) (**Table 1**).
  iii. Assign values for each bridge based on the following ranges.

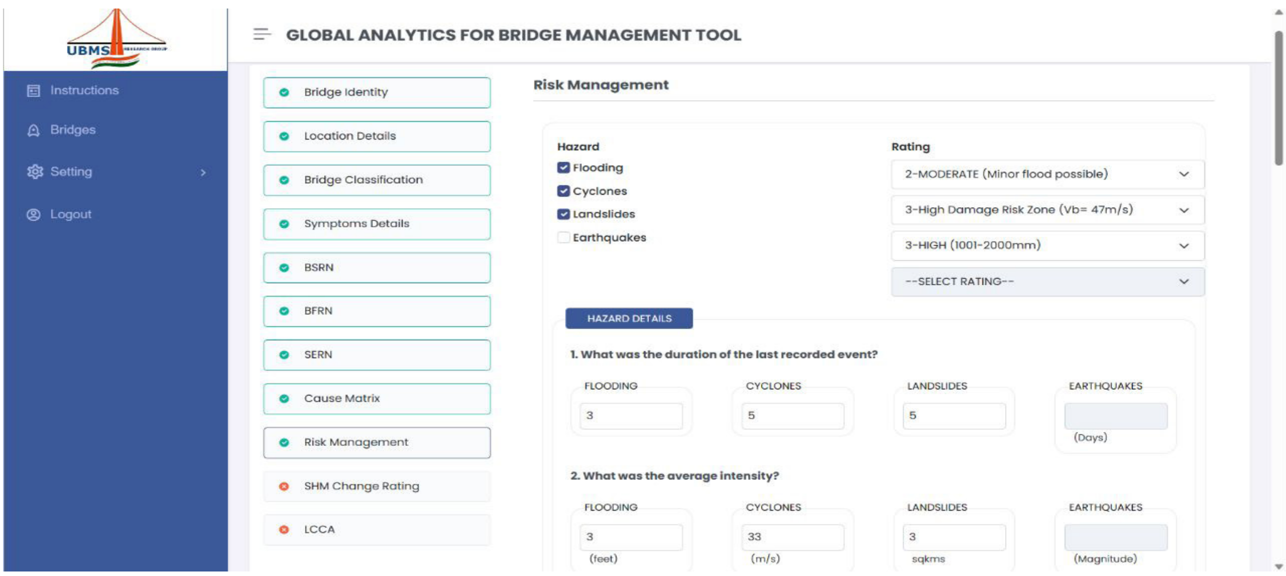

Figure 1A. GABM identify hazards.

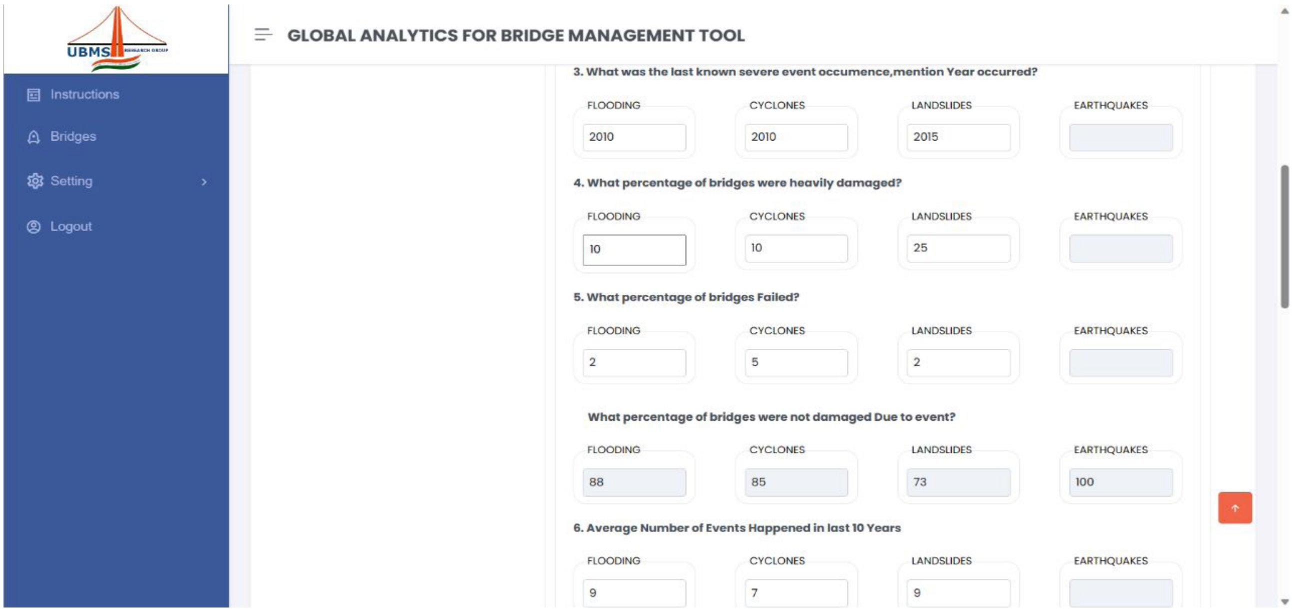

Figure 1B. GABM data collection.

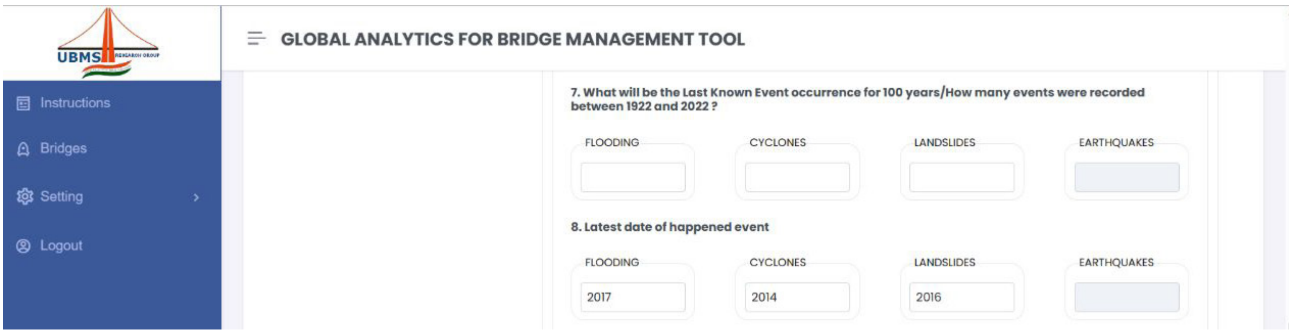

Figure 1C. GABM's latest occurrence.

Table 1. Likelihood of service disruption (LDbh).

Likelihood of service disruption (LDbh)		
Range	Probability	Values
Good	< 5%	0
Satisfactory	< 35%	25
Poor	< 65%	50
Critical	< 95%	75
Failed	>= 95%	100

- Quantify vulnerability factors using engineering analysis and historical data.

2.4 Risk indices

- Evaluate the Risk index for the bridge by multiplying utility by the vulnerability.
- The highest values of the Risk index will be prioritised for rehabilitation and repair (**Figure 1D**).

The risk index quantifies the probability and severity of a natural hazard occurring at a particular location. The risk index considers factors such as the probability of hazard occurrence, the intensity of the hazard, distance from the epicentre and the vulnerability of the population and infrastructure in the area. The risk index can be used to identify areas that are most vulnerable to natural hazards, prioritize mitigation measures, and evaluate the effectiveness of emergency response plans. The risk index is specific to the type of natural hazard. The index will be different for earthquakes, landslides, flooding, cyclone, extreme temperature, or any other hazard (**Figure 2**).

The development of risk indices for hazards has become an essential component of hazard research and management. Risk indices have been used in the

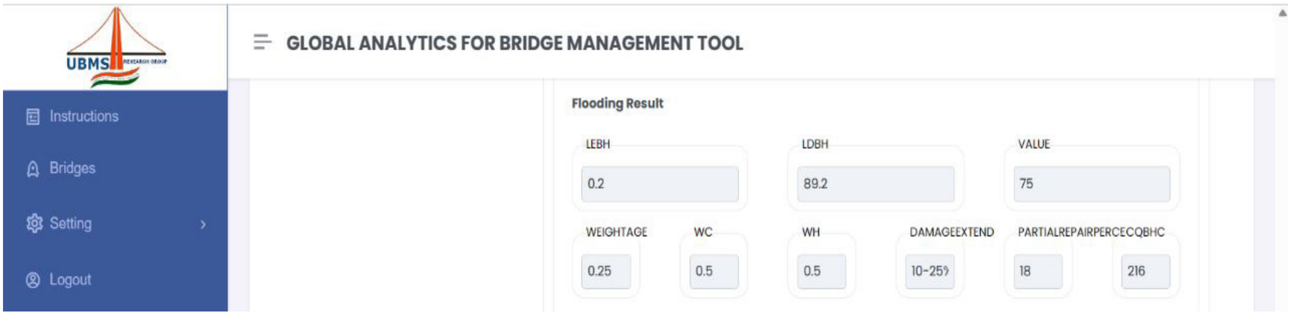

Figure 1D. Results of risk management in GABM.

Figure 2. Bridge damage due to flooding hazard.

assessment of all major natural hazards including earthquakes, floods, cyclones, landslides, and similar hazards. In each of these applications, the risk index provides a quantitative measure of the risk of a hazard occurring in a particular location and helps to identify areas that are most vulnerable to natural hazards [12].

The natural hazard module aims at the utilization of risk indices for the natural hazards in the GABM application. Specifically, the module is focused on the methodology and usage of the risk indices for natural hazards in bridge management. The establishment of a risk index for hazards entails the use of mathematical models to quantify the likelihood and severity of a hazard occurring in a specific location.

The risk index is used to assess the potential risks associated with bridges. This index combines information on the likelihood of the event occurring, its intensity, its proximity to the bridge and the consequences of that event. By considering all the factors, bridge managers can prioritize their resources and take appropriate actions to mitigate risks effectively during the decision-making process. The likelihood of the event occurring refers to the probability or frequency of the event occurring. For example, a bridge located in an area prone to earthquakes would have a higher likelihood of experiencing a seismic event compared to a bridge located in a seismically stable region.

To develop a risk index, the module typically evaluates and assigns numerical values or ratings to the likelihood, intensity, proximity, and consequences of various events (**Figure 3**). These ratings can be based on historical data, expert opinions, or analytical models [10]. For example, likelihood ratings can be categorized as low, medium, or high, while consequence ratings can be classified as minor, moderate, or severe.

Once all the ratings are assigned, they are combined using a predetermined formula to calculate the risk index for each risk event. This formula can be as simple as multiplying the likelihood and consequence ratings together, or it can involve more complex mathematical calculations or statistical models. The resulting risk index provides a quantitative measure of the overall risk level associated with

Figure 3. Bridge damage due to seismic hazard in the corrosion-prone bridge.

each risk event. GABM uses a mathematical model to evaluate the risk index. Based on the risk index, bridge managers can prioritize their efforts and allocate resources accordingly. The fund optimization module enables the bridge manager to reach the objective. Risk events with higher indices indicate a greater need for immediate attention and mitigation measures. This allows the development of risk mitigation and management strategies, such as conducting regular inspections, implementing maintenance programs, or prioritizing repair or replacement projects for bridges with the highest risk levels.

Utilizing the risk index enables informed decisions to initiate proactive steps to ensure the safety and longevity of bridge infrastructure. Mitigation principles involved are also based on taking a more proactive approach towards the vulnerability of the bridge to a particular hazard (**Figure 4**) [13].

The protocol enables bridge management to address the various issues involved more efficiently and effectively. We all understand that damage arising due to hazards cannot be avoided but an attempt to restrict the damage is initiated.

Risk assessment is an integral part of bridge sustainability, facilitating the identification and prioritization of hazards. Quantitative and qualitative risk assessment models are utilized to evaluate the vulnerability of bridge structures to natural hazards. By conducting comprehensive risk assessments, bridge authorities can prioritize mitigation efforts, allocate resources effectively, and implement adaptive strategies to reduce vulnerabilities. The sustainability of bridges can be further enhanced through the implementation of targeted mitigation measures. These may include retrofitting vulnerable components, employing innovative construction materials, and implementing advanced design principles that consider hazard resilience. Additionally, incorporating

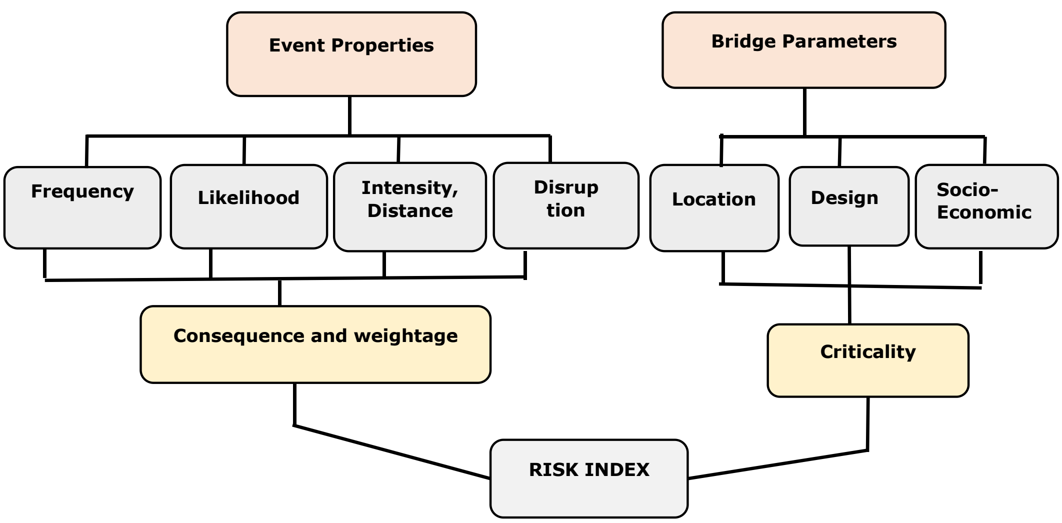

Figure 4. Risk index evaluation flow chart.

nature-based solutions, such as vegetation barriers and erosion control measures, can enhance the durability and sustainability of bridges while promoting environmental compatibility.

Bridge sustainability, environmental, social, and economic considerations are crucial. Furthermore, engaging local communities in decision-making processes and considering their needs and concerns promotes social sustainability. Finally, conducting life cycle cost analyses helps bridge authorities assess the economic feasibility of sustainable practices and make informed decisions regarding long-term maintenance and rehabilitation strategies.

BETA testing for the evaluation of Risk Indices for various hazards and geography is undertaken and the results of this have been utilized to modify/correct the procedures (**Figure 5**).

3. Results

The benefits that can accrue are not possible without the below-listed processes [14-16]:

Data Integration: GABM integrates various data sources related to bridge infrastructure, hazard occurrences and characteristics, and vulnerability assessments.

Risk Assessment Modelling: Utilizes advanced risk assessment models to quantify individual risk hazards. These models consider factors such as hazard probabilities, hazard intensities, proximity to past occurrences, bridge vulnerability, and potential consequences.

Hazard Mapping: Incorporates individual hazard mapping and can present the spatial distribution of various risk hazards. For example, one bridge could be more vulnerable to earthquakes and less or not vulnerable at all to floods and cyclones (**Figures 6 and 7**).

The resulting benefits to the region and bridges on the network are many. The below listing is the key benefits only. Many other ancillary benefits can culminate.

1) Comprehensive Risk Assessment: GABM provides a holistic, quantitative, and qualitative as-

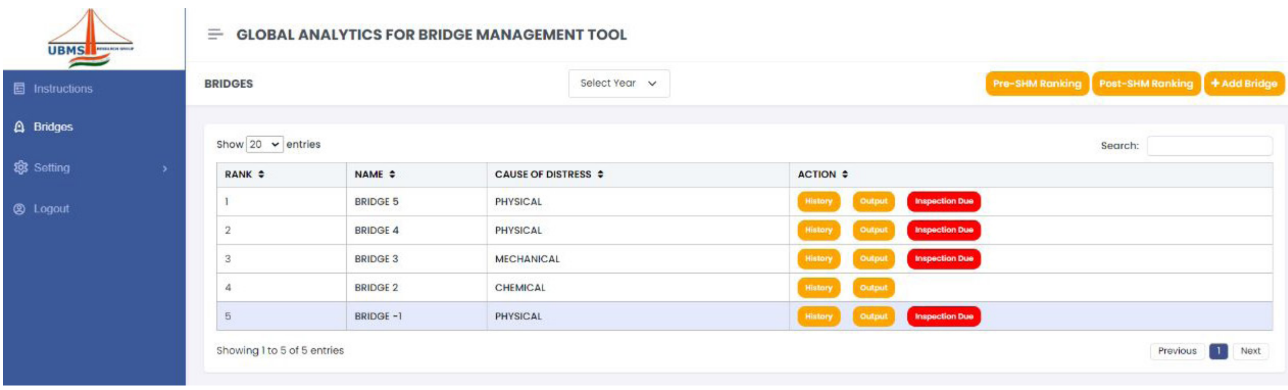

Figure 5. Recorded bridges in GABM.

Figure 6. Cyclone impact on bridges.

Figure 7. Concrete degradation of the bridge due to continued exposure to flood hazard.

sessment of risk by considering multiple hazards, bridge vulnerabilities, and potential consequences.

2) Prioritization of Resources: Allows users, to prioritize resources based on the level of risk.

3) Efficient Risk Mitigation: Implement targeted and cost-effective risk reduction measures.

4) Cost-Benefit Analysis: Helps in cost-benefit analyses for bridge management and maintenance.

5) Comprehensive Risk Assessment: Holistic, quantitative, and qualitative assessment of risk by considering multiple hazards, bridge vulnerabilities, and potential consequences.

6) Improved Decision-Making: Provides a standardized measure that can be used for comparative analysis and decision-making.

7) Enhanced Emergency Response Planning: During hazard events, it enables quick identification of bridges at higher risk, helping them prioritize emergency response efforts.

8) Long-Term Planning and Resilience: Supports long-term planning.

9) Stakeholder Communication: Provides a clear and easily communicable measure of risk. It facilitates effective communication with all stakeholders.

4. Conclusions

The information presented in this paper highlights the devastating impact on human life and infrastructure due to sporadic and erratic natural hazards, particularly in the context of recent events around the world. It emphasizes the urgency to adopt a proactive approach to managing natural hazards, with a focus on bridges' vulnerability, given their critical role in transportation networks. The paper introduces the Risk Index for hazards as a valuable tool to quantify the probability and severity of natural hazards occurring in specific bridge locations. The integration of risk indices within GABM is emphasized, as it provides a systematic and data-driven approach to assess and mitigate risks associated with hazards in bridge management. The integration's main contributions include providing an informed decision-making option for prioritization of resources, efficient risk mitigation, and enhancing the resilience of bridge infrastructure. The risk index results enable the ranking of bridges based on their risk levels. This ranking provides a clear understanding of which bridges are at higher risk and require immediate attention in terms of mitigation measures, maintenance actions, or resource allocation. This ranking is based on the Engineering Impact Index and Financial Impact Index which quantify the effects of deterioration on engineering performance and financial costs associated with repairs or replacement, Sustainability Index assesses the environmental and social sustainability aspects of the bridges. The Risk and Hazard Index represents the level of risk associated with the specific hazards that bridges may face, and Final Cost Index combines all four indexes using a standard ratio, to provide an overall assessment of the cost implications associated with the bridge projects.

The research highlights the benefits of conducting comprehensive risk assessments, engaging in long-term planning, and considering environmental and social sustainability aspects in bridge management. By utilizing risk indices, bridge managers can take proactive steps to address vulnerabilities and allocate resources efficiently, ultimately leading to the safety and sustainability of bridge networks in the face of natural hazards. By incorporating data on hazard occurrences, bridge vulnerability, and potential consequences, it facilitates a comprehensive assessment of individual risk hazards, enabling bridge managers to prioritize resources and implement targeted mitigation strategies. GABM's scenario analysis and decision-making support feature further enhances its effectiveness in evaluating different mitigation measures and improving bridge performance.

Future research directions in this area could focus on refining and expanding the risk assessment models to encompass a broader range of natural hazards and bridge types. The development of more sophisticated risk indices that consider additional factors such as climate change projections, soil conditions, and structural materials would enhance the accuracy and effectiveness of risk evaluations.

Additionally, further research could explore the integration of real-time data and advanced sensor technologies into the risk assessment process. By incorporating real-time data on weather patterns, water levels, and seismic activity, bridge managers could have a more dynamic and responsive approach to risk management, enabling them to take timely preventive measures during hazardous events. This approach can lead to improved emergency response planning, quicker identification of high-risk bridges during hazardous events, and better coordination with emergency management agencies.

Bridge managers can use risk indices to conduct cost-benefit analyses for various mitigation strategies. By considering potential risks and associated costs of bridge failures or disruptions, informed decisions can be made regarding investments in maintenance, repair, and retrofitting, which contributes to the overall safety and longevity of bridge networks. It is essential to acknowledge the potential limitations of using risk indices for bridge management and risk assessment. Future research directions and practical implications should be discussed. Limitations may include uncertainties in data quality, modelling assumptions, and challenges in real-world implementation. Addressing these limitations and further research on refining risk assessment methodologies will be crucial for enhancing the practical applicability of risk indices and ensuring their effectiveness in real-life scenarios.

Conflict of Interest

There is no conflict of interest.

References

[1] Asrani, N.P., Venkatasubramanian, C., Muthu, D., et al., 2018. Risk management â€" decision making using analytical hierarchy process. International Journal of Engineering & Technology. 7(3.12), 188.
DOI: https://doi.org/10.14419/ijet.v7i3.12.15917

[2] Rahman, J., Billah, A.M., 2023. Development of performance-based fragility curves of coastal bridges subjected to extreme wave-induced loads. Journal of Bridge Engineering. 28(3), 04023005.

[3] Patel, K., 2013. A study on risk assessment and its management in India. American Journal of Civil Engineering. 1(2), 64-67.

[4] Pablo Jr, R.M., 2009. Risk assessment of highway bridges: A reliability-based approach. The Technology Interface Journal. 10(2), 165-172.

[5] Heldt, T., 2019. Enabling Better Bridge Management by Understanding Risk by Tim Heldt [Internet]. Available from: http://ipweaq.intersearch.com.au/ipweaqjspui/handle/1/5378

[6] Thompson, P.D., Western, J., Bye, P., et al., 2016. Assessing Risk for Bridge Management: Final Report [Internet]. Available from: https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP2007Task378FinalReport.pdf

[7] Kameshwar, S., Padgett, J.E., 2014. Multi-hazard risk assessment of highway bridges subjected to earthquake and hurricane hazards. Engineering Structures. 78, 154-166.

[8] Banerjee, S., Ganesh Prasad, G., 2013. Seismic risk assessment of reinforced concrete bridges in flood-prone regions. Structure and Infrastructure Engineering. 9(9), 952-968.

[9] Joshi, S., Thorat, A., Dehadray, H., et al., 2023. GABM tool for Risk Mitigation of Natural Hazards of Bridges [Internet]. Available from: https://constrofacilitator.com/gabm-tool-for-risk-mitigation-of-natural-hazards-of-bridges/

[10] Asprone, D., Jalayer, F., Prota, A., et al., 2010. Proposal of a probabilistic model for multi-hazard risk assessment of structures in seismic zones subjected to blast for the limit state of collapse. Structural Safety. 32(1), 25-34.

[11] Akintoye, A.S., MacLeod, M.J., 1997. Risk analysis and management in construction. International Journal of Project Management. 15(1), 31-38.

[12] Raupach, M., Büttner, T., 2014. Concrete repair to EN 1504: Diagnosis, design, principles and practice. CRC Press: Boca Raton.

[13] Risk and Hazard Management [Internet]. Available from: https://www.otago.ac.nz/health-safety/hazards/

[14] Amiri, M.J.T., Abdollahzadeh, G., Haghighi, F., et al., 2019. Bridges risk analysis in view of repair and maintenance by multi criteria decision making method (case study? Babolsar Bridges). International Journal of Transportation Engineering. 7(1), 91-114.

[15] Choudhry, R.M., 2019. Risk analysis related to cost and schedule for a bridge construction project. Perspectives on risk, assessment and management paradigms. IntechOpen: London.

[16] Alfieri, L., Cohen, S., Galantowicz, J., et al., 2018. A global network for operational flood risk reduction. Environmental Science & Policy. 84, 149-158.