GUIDELINES FOR IMPLEMENTATION OF RISK AND VULNERABILITY ANALYSIS FOR BRIDGES

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ABSTRACT:

Globally we face the herculean task of avoiding the impact of climate change and dynamism in natural hazard severity and frequency. United Nation office for Disaster Risk Reduction [UNDRR] created awareness towards avoidance of natural hazard and climate change impact from becoming calamities or disasters.

Bridge fraternity by and large, has so far maintained their distance and not proactively associated with such efforts. UBMS Research Group [URG] is a beacon fully dedicating their research to the efforts of UNDRR within the limited domain of Bridge management.

URG's focus on Bridge Management Systems [BMS] has seen humongous changes in availability of Knowledge base in public domain. BMS implementing authorities now can define the risk and vulnerability of bridges to natural hazard events.

Globally, many governments are now responding to the need and urgency of restricting carbon emissions to required limits adopted at the COP21 in Paris, France, in 2015. Countries have adopted or evolved Net Zero Roadmap and Action plans to limit Carbon emission and embodied carbon emission.

BMS needs to align with such efforts. It involves usage of natural materials, robust and resilient bridge design, construction and maintenance strategies. It is with this backdrop URG is putting forward this **"Guidelines for Implementation of Risk and Vulnerability Analysis for Bridges"**.

These Guideline define the Concept of risk and vulnerability of bridges, and how the climate change and natural hazards occurrences impact the bridges. This leads to evaluation of exposure conditions and deterioration process being involved in risk and vulnerability analysis. Evaluation of risk heavily depends on the natural hazard. It results in principle to define the priority for fund allocation. Enhancement in resilience yields sustainability. Finally the procedure to adopt the Net Zero Roadmap and Action plans to limit Carbon emission and embodied carbon emission.

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ABRIDGED SUMMARY

"**Guidelines for implementation of Risk and Vulnerability Analysis for Bridges**" is compiled by UBMS Research Group [URG].

URG has been involved in research in the domain of Bridge Management System [BMS] for over two decades. URG's research has provided world's first Fully Digitised Bridge Management System in the year 2012. This was implemented in India as IBMS which collated data for over 172,000 bridge structures for over four years from 2015.

Post 2020, URG's team integrated Cause matrix and Short-term SHM [apart from symptoms] to evaluate Balance Service Life [BSL] and Absolute BSL which resulted in real-time evaluation of deterioration model. Life Cycle Cost Analysis was integrated to enable financial due diligence in the decision-making processes.

Subsequently URG aligned with the goals of the United Nations office of Disaster Risk Reduction [UNDRR]. URG's focus now include Disaster Risk Reduction and Resilience in Bridges. Risk assessment for four main Natural Hazards was included within the BMS. In 2021, URG made a voluntary commitment to evolve a tool that will enhance the resilience of existing deteriorated bridges in the high risk zones for natural hazards using Global Analytics for Bridge Management.

[https://sendaicommitments.undrr.org/commitments/20231017_001]

This Voluntary Commitment given to UNDRR under Sendai Framework was completed in 2024. During the course of our research, URG persistently provided all their research documentation in open forum. Our website [https://ubmsresearchgroup.com] has most important research papers available for downloading.

This Guideline document is also available in open forum on our website.

This guideline has six chapters.

Chapter One deals with the need to implement Risk and Vulnerability analysis [RVA]. It elaborates on the factors leading to collapse of resilience and sustainability.

Chapter Two deals with the concept of Risk and Vulnerability in bridges. Defines the key aspects within RVA. Focuses on the objectives of RVA. The needs to have a national approach to avoid fragmented RVA. Further exemplifies the factors affecting RVA in bridges.

Risk in bridges is the probability of a hazard occurring combined with its consequences such as structural damage, service disruption, or socio-economic losses. Key elements of Risk and Vulnerability Assessment [RVA] include hazard, exposure, and vulnerability. The interplay of these factors determines the actual level of risk, which evolves dynamically due to ageing infrastructure and climate change. RVA aims to identify weaknesses, quantify risks, guide adaptation measures, and support policy for resilient infrastructure. Local RVA efforts are useful but limited, making National RVA framework essential for standardisation, integrated data-sets, better hazard prediction, and coordinated resilience planning. Without it, assessments remain fragmented, resources wrongly allocated, and critical bridges exposed to large-scale disruptions. Ultimately, effective RVA ensures operational resilience, long-term safety, and uninterrupted connectivity of critical lifeline bridges during disasters.

Chapter Three introduces the concept of how the climate change and natural hazard impact bridges. Includes the outline of the design philosophy and the limitation of having a static approach in a dynamic scenario. Focus on the dynamism in natural hazard and climate change and the impact of this dynamism.

Bridges are designed for long service life for design loads, now face increasing challenges from climate variability and natural hazards that often exceed assumptions. Traditional design codes, while robust, do not account accurately for the growing frequency and intensity of extreme events. Ageing bridges undergo deterioration due to environmental factors and human induced factors. So such ageing bridges become highly vulnerable when exposed to natural hazard in hazard prone regions. Failures often occur through hydraulic mechanisms like scouring, seismic impacts like soil liquefaction, or climatic stresses like wind-induced instability and thermal cracking. The situation is further worsened by multi-hazard interactions, where forces of multiple hazard combine. This highlights the urgent need for continuous inspections, retrofitting, and climate-adaptive design approaches to ensure resilience and safety of bridge infrastructure in a changing environment.

Chapter Four defines the impact and significance of two key factors of exposure condition and bridge deterioration and their synergy.

The evaluation of bridge vulnerability depends on two dimensions—exposure condition and deterioration status. Exposure reflects the natural hazard environment, shaped by historical frequency and severity, while also accounting for dynamic climate change trends that prove extreme events more frequent and intense. To standardise assessments, zones are defined by climate and hazard profiles, with exposure is further influenced by geo-spatial boundaries, inter-connectivity within transport networks, and socio-economic importance. Deterioration, on the other hand, captures the internal health of a bridge, structural distress, ageing effects, and maintenance history. These are evaluated during bridge inspection procedure. The combined effect of exposure and deterioration defines three age related service life parameters: Balance Service Life [BSL], Absolute Balance Service Life [ABSL], and Median Service Life [MSL], the critical threshold beyond which the bridge is unsafe and requires replacement or reconstruction. This integrated framework ensures that risk assessments capture both external hazard pressures and the internal resilience of bridge structures.

Chapter Five outlines the fundamentals of an efficient RVA. Limitation of historical data relating to climate and the impact of data unavailability. Emphasis is on the dependence of Risk on Vulnerability and exposure scenario.

Risk and Vulnerability Analysis [RVA] the foundation for assessing the resilience and reliability of bridge infrastructure under multiple hazard conditions integrates hazard exposure, structural vulnerability, and functional importance to evaluate the probability and consequences of failure. Risk defined as the likelihood of loss when a bridge is exposed to natural or man-made hazards, while vulnerability represents the inherent weaknesses that make the bridge susceptible to damage. Together, they determine the potential for structural failure, connectivity loss, and socio-economic disruption. Bridge risk evolves over time due to ageing, material deterioration, and the intensifying effects of climate change. Criticality of the bridges that serve as lifelines during rescue and relief operations, needs attention. Historical climate and hazard data form the backbone of risk assessment, providing essential insights into event frequency, severity, and return periods for scientific standardisation of exposure analysis. RVA integrates hazard identification, exposure mapping, vulnerability assessment, and the recognition of critical routes essential for regional connectivity and emergency response. Evaluation of vulnerability involves both physical [structural condition, material degradation] and functional [traffic importance, network dependency] aspects. The risk evaluation process then synthesise these factors to categorise bridges into low, moderate, high, or critical risk levels. RVA guides decision-making and prioritization in bridge management. High-risk bridges on critical routes require immediate retrofitting or replacement, while moderate- and low-risk bridges demand structured maintenance and monitoring. By translating scientific data into actionable outcomes, RVA acts as a strategic tool for disaster resilience, policy formulation, and sustainable infrastructure planning, ensuring that vital transportation links remain operational during and after hazard events.

Chapter Six defines the concept of critical conditions and risk indicators. How the exposure [likelihood of natural hazard occurrence] is linked to severity of event, deterioration status of bridge are defining the RVA in bridges. Emphasis on the priority considerations, Need for Zero Carbon path and few modern technologies to enhance resilience in bridges are outlined.

Bridges are among the most critical elements of transportation infrastructure, serving as lifelines that support the safe and efficient movement of people, goods, and essential services. They not only provide connectivity between regions but also enable access to healthcare, education, trade, and emergency relief, making them indispensable for social and economic stability. Yet, the reality across the globe is that bridge inventories are ageing, with a significant proportion of existing structures having already surpassed their intended design life. This ageing infrastructure has become a growing concern, as older bridges require more frequent inspection, rehabilitation, and management to ensure they remain functionally safe. Without proactive measures, ageing bridges face increased risk of deterioration leading to imminent failure. Bridge failure potentially causes disruption to the entire transportation networks, posing a direct threat to public security and safety.

The process of bridge deterioration is inevitable, driven by both material and environmental factors. From the time concrete is cast, it gets exposed to vagaries of nature. Over time, concrete suffers from carbonation and chloride ingress. This accelerates steel reinforcement corrosion. Incessant traffic loads create fatigue cracks that reduce structural integrity. Inadequate drainage, poor maintenance practices, and design limitations further accelerate the decline of structural performance.

Compounding these issues, many older bridges witness higher levels of traffic or the axle loads common today, meaning they

are consistently subjected to stresses that exceed their original design assumptions. As a result, ageing bridges become increasingly prone to distress, ranging from surface defects such as spalling and cracking to more severe structural problems such as fatigue, settlement or functional obsolescence.
Adding to this challenge is the accelerating impact of climate change and natural hazards. Traditionally, bridge design accounted for routine climate exposure and hazard occurrences within predictable ranges. Such predictable range was and is determined by historical climate and natural hazard occurrence data. The intensifying frequency, severity, and unpredictability of extreme events [example: floods, cyclones, earthquakes, and landslides] subject the bridge to stresses beyond the range it has been designed for.

Flooding events can erode foundations through scour, cyclones can induce fatigue and damage to superstructures, earthquakes cause horizontal stresses on sub and superstructure, and temperature fluctuations can cause excessive expansion and contraction in materials. These evolving conditions are forcing bridge infrastructure to perform under circumstances that were rarely anticipated during their initial design stage. In many cases, the compounding effects of climate variability are not only accelerating deterioration but also creating entirely new vulnerabilities, underscoring the urgent need for adaptive and forward-looking solutions.

This brings into importance Resilience in bridges. Bridges are not simply conduits for vehicles; they represent essential links that sustain communities and economies. Their failure can lead to isolation of entire populations, disruption of supply chains, delays in emergency response, and prolonged recovery in the aftermath of disasters. Ensuring that bridges are resilient [that they can withstand hazards, recover quickly from disruptions, and continue to function effectively] is essential for minimising the socio-economic consequences of disasters. Resilient bridges maintain continuity of services and connectivity, reinforcing public security resulting in sustainability, safety and enhancing disaster preparedness.

Economic consideration during conceptualisation, design and construction stage has resulted in our bridge structure being constructed to minimum codal requirements. Such minimum requirements are safe under normal scenarios. Dynamism in natural hazards and climate change has resulted in an unsafe scenario. Robustness and resilience during design and construction stage is missing.

In face of emerging scenario where dynamism in climate change and natural hazard occurrence frequency and severity coupled with the ageing demography of bridges, enhancing and establishing resilience in critical bridges is essential and very important. Many past research by reputable organisations have illustrated that investing one dollar in resilience and precautionary measures yield over 4 to 8 times more in returns and also avoids immediate loss in short and long term.

The convergence of an ageing bridge inventory, natural deterioration processes, and intensifying climate and hazard risks calls for a paradigm shift in how bridges are planned, designed, and managed. It is no longer sufficient to focus on short-term functionality or to rely on traditional maintenance practices. Instead, a holistic approach is required—one that integrates risk and vulnerability evaluation, proactive maintenance strategies, resilience-oriented design, and sustainable management practices. Only by adopting such a comprehensive framework can bridges continue to serve as safe, reliable, and enduring lifelines that support both present and future generations.




Resilient bridges result in maintenance of required connectivity. Sustainability is ensured. Resilience and Sustainability go hand in hand. Resilience enhances and reinforces the security within the society. A secure society enables continued economic growth and stability. Socioeconomic fabric of the society is stable resulting in sustainability of that society and region. Rebound capacity of the society is high and downtime due to temporary inconvenience is quickly overcome. This important property in the society results in long term sustainability. Resilience therefore helps to enhance the sustainability.

The systematic evaluation of bridge risk and vulnerability represents a cornerstone in achieving resilient infrastructure and sustainable disaster management. Bridges play a pivotal role in maintaining socio-economic stability by connecting regions, facilitating trade, ensuring mobility, and providing critical access during emergencies. Their significance extends far beyond engineering performance—they serve as lifelines that sustain communities, economies, and emergency operations. However, in recent years, the growing intensity of natural hazards such as floods, landslides, earthquakes, and cyclones—amplified by climate change—has increased the exposure and fragility of these vital assets. Consequently, an integrated, science-based framework for assessing, prioritizing, and managing bridge vulnerability has become essential for long-term infrastructure resilience and disaster preparedness.

The overall framework developed during research bridges the gap between traditional engineering inspection methods and modern risk-based approaches. It recognizes that risk is a multi-dimensional concept arising from the dynamic interplay between hazards, exposure, and vulnerability. Hazards represent the potential threats from environmental or geotechnical events; exposure defines the extent to which bridges and related assets are located within these hazard zones; and vulnerability expresses the sensitivity of structures and communities to those threats. This triad forms the foundation for understanding not only the physical condition of bridges but also their contextual importance and adaptive capacity.

Through this analytical lens, the study introduces a methodology that begins with hazard identification and exposure mapping, followed by a detailed evaluation of structural vulnerability and socio-economic dependency. By integrating historical hazard data, geospatial mapping, and field inspections, it becomes possible to determine which bridges are at greater risk due to their location, age, material degradation, or poor maintenance. Furthermore, bridges that form part of key economic corridors, emergency access routes, or densely populated regions are classified as “critical” because their disruption would cause extensive socio-economic consequences. This nuanced approach ensures that risk evaluation is both technically precise and socially relevant.

Central to the framework is the Risk Indicator Matrix, a decision-support tool that combines multiple dimensions—likelihood of hazard occurrence, severity of impact, and structural deterioration status—to produce quantifiable risk scores. Each bridge is assessed against predefined indicators related to its physical condition, foundation stability, hydraulic vulnerability, and surrounding topography. Simultaneously, its importance to local economies, transportation continuity, and disaster response operations is factored into the evaluation. The resulting matrix not only classifies bridges into low, medium, or high-risk categories but also guides authorities in prioritizing rehabilitation and retrofitting measures based on objective, data-driven evidence. This ensures that limited financial and technical resources are directed to where they are most needed and can generate the highest resilience benefits.

The evaluation of vulnerability extends beyond structural deficiencies to include institutional and community capacities. It considers the presence of maintenance programs, frequency of inspections, availability of emergency funds, and accessibility of alternate routes. In doing so, it introduces the concept of adaptive capacity, which determines how effectively a bridge system and its managing institution can anticipate, withstand, and recover from hazards. This holistic understanding transforms vulnerability assessment from a static structural exercise into a dynamic resilience evaluation, linking engineering parameters with governance, preparedness, and social inclusion.

A crucial outcome of this work is the establishment of priority considerations derived from the RVA [Risk and Vulnerability Assessment] process. Priority, in this context, is defined by the convergence of high risk, high exposure, and high socio-economic criticality. A bridge that is structurally sound but essential for disaster response may receive equal or higher priority compared to an older but less significant bridge. The process of defining priorities thus involves balancing technical, operational, and humanitarian factors through structured evaluation. This leads to transparent, dependable decision-making, ensuring accountability in infrastructure management and investment planning.

Furthermore, the study emphasises the need for continuous monitoring, stakeholder engagement, and data integration. Risk is not static; it evolves with environmental change, urban expansion, and infrastructural ageing. Therefore, the proposed methodology advocates for periodic reassessment using updated data and emerging technologies such as remote sensing, GIS-based exposure mapping, and sensor-based structural health monitoring. Engaging local authorities, engineers, community representatives, and disaster response agencies ensures that the RVA process remains inclusive, credible, and reflective of ground realities.

In a broader sense, this comprehensive approach aligns with global frameworks such as the Sendai Framework for Disaster Risk Reduction [2015-2030] and national DRR initiatives, reinforcing the transition from reactive post-disaster repair to proactive risk management and resilience building. It advocates a paradigm shift—where maintenance and rehabilitation decisions are not driven solely by physical deterioration but by the strategic understanding of risk, vulnerability, and socio-economic dependency.

Ultimately, RVA enables us to conclude that bridges must be evaluated and managed as integral components of resilient transportation networks, rather than as isolated engineering structures. By combining technical assessments with socio-economic, environmental, and institutional dimensions, the MCDM framework developed here provides a powerful tool for sustainable infrastructure planning. It empowers decision-makers to set priorities transparently, allocate resources efficiently, and design interventions that safeguard both assets and the communities that rely on them.

This integrated approach ensures that the bridges of tomorrow will not only withstand physical stresses but also enhance connectivity, security, and resilience in the face of growing climatic and geotechnical challenges. Through continuous evaluation, adaptive management, and evidence-based prioritization, this methodology lays the foundation for a future where infrastructure serves not only as a means of transport but as a pillar of safety, stability, and sustainable development.