GUIDELINES FOR IMPLEMENTATION OF RISK AND VULNERABILITY ANALYSIS FOR BRIDGES

RESEARCHED AND CONCEPT BY

UBMS RESEARCH GROUP

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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] is creating 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 one of the beacon fully dedicated their research to the efforts of UNDRR.

URG’s focus on Bridge Management Systems 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 such 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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CHAPTER ONE:

INTRODUCTION:

"**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 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 decision-making processes.

Subsequently URG aligned with United Nations office of Disaster Risk Reduction [UNDRR]. URG's focus then included Disaster Risk Reduction and Resilience in Bridges. Risk assessment for four main Natural Hazards was included within the BMS[1].

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 has 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.

Chapter Three introduces the concept of how the climate change and natural hazard impact bridges. Outlines 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.

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

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

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. Outlines the priority considerations, Need for Zero Carbon path and few modern technologies to enhance resilience in bridges.

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 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 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[2].

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 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[3]. 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.

URG pioneers in Bridge Management System [BMS] providing the world's first fully digitised BMS, has advanced bridge evaluation through BSL modelling, LCCA, and resilience-focused tools under the UNDRR Sendai Framework. Bridges are vital lifelines for connectivity, trade, healthcare, and emergency services. Globally, bridges are ageing and deteriorating due to material degradation, overloading, poor maintenance, and inadequate design standards. Climate change and intensifying natural hazards makes resilience a necessity. Traditional approaches are insufficient in today's dynamic hazard environment. A resilience- and sustainability-oriented framework is essential to ensure reliability.

CHAPTER TWO:

CONCEPT OF RISK AND VULNERABILITY OF BRIDGES

Key Definitions within RISK AND VULNERABILITY ANALYSIS [RVA]

In the context of bridges, **Risk** is defined as the probability of a hazardous event occurring combined with the consequences that follow, such as structural failure, service disruption, or socio-economic losses.

Vulnerability refers to the inherent weaknesses within the bridge system that make it more susceptible to damage when exposed to hazards. These weaknesses may arise from material degradation, inadequate design standards, lack of maintenance, or ageing infrastructure. **Hazard** itself represents the potential occurrence of a damaging event, either climatic [such as heavy rainfall, floods, or extreme heat] or geophysical [such as earthquakes and landslides].

Exposure denotes the degree to which a bridge is located in hazard-prone zones, for example, a river-crossing bridge in a floodplain or a mountain bridge in a landslide-prone area[4].

Another important term is **Balance Service Life**, which refers to the remaining operational years of a bridge before it reaches a critical point where its safety and functionality could be compromised.

Moreover, the impact of hazards on bridges may manifest in multiple ways: direct physical damage to the structure, deterioration of materials due to climatic stress, or indirect effects such as traffic disruption and economic losses in the connected regions. Clearly defining these terms within RVA provides a scientific foundation for assessing bridge safety and resilience.

To eliminate ambiguity, it is essential to differentiate between closely related terms.

Hazard vs. Risk: Hazard is the potential occurrence of an event, risk emerges when a hazard interacts with exposure and vulnerability. For example, a flood is a hazard, but the risk to a bridge arises when that flood coincides with poor drainage design and an exposed location.

Hazard vs. Threat: A threat is the likelihood of a hazard becoming an actual damaging event.

Adaptation vs. Mitigation: Adaptation refers to structural and functional adjustments [example: elevating bridge decks to reduce flood risk], while mitigation addresses the root causes of climate hazards, such as reducing carbon emissions.

Adaptation vs. Risk and Vulnerability Management: Adaptation is proactive, preparing the structure for anticipated hazards, whereas Risk and vulnerability management encompasses a broader process of identifying, assessing, and reducing risks through policies, maintenance, and emergency responses.

These distinctions provide clarity in developing effective strategies, ensuring that actions such as response, mitigation, and recovery are not misinterpreted but aligned within a structured RVA framework[5].

Objectives and Focus of RVA

The objectives of RVA must extend beyond broad goals like sustainability and instead **emphasize operational resilience**. The primary objective is to ensure that bridges remain functional during and after hazard events, thereby safeguarding connectivity for life-saving rescue and relief operations. The specific objectives include:

- Identifying vulnerabilities in bridge structures under climate and natural hazard conditions.
- Quantifying risks to prioritise interventions.
- Guiding adaptation measures to extend the balance service life of bridges.
- Supporting policy decisions for investment in resilient infrastructure.

The outcomes of RVA are measurable and include increased structural reliability, reduced disruption during disasters, and enhanced preparedness. However, several challenges exist, such as incomplete hazard data, difficulty in predicting future climate dynamics, financial constraints, and variations in local capacity for implementation. Addressing these challenges is critical for translating RVA into practical resilience strategies.

Need for National RVA Principle

Local and regional Risk and Vulnerability Assessments [RVA's] provide valuable insights into bridge-specific or area-specific hazards. However, their effectiveness is fundamentally limited because natural hazards do not conform to administrative or political boundaries. Floods, cyclones, earthquakes, and landslides often extend across multiple states or even countries, with cascading impacts that exceed the scope of localized assessments. For instance, a single flood in a large river basin can simultaneously damage hundreds of bridges across different states, disrupting both regional connectivity and national supply chains. Such realities highlight the inadequacy of fragmented RVA approaches in addressing large-scale risks[6].

A National RVA framework is indispensable because it provides a coherent and standardized approach applicable across diverse geographical and climatic conditions. Unlike regional assessments, which often operate in silos, a national framework:

- **Standardizes methodologies** - ensuring that assessments conducted across states use uniform definitions, metrics, and procedures.

- **Integrates datasets** - combining hydrological, meteorological, geological, and socio-economic data for a comprehensive analysis.

- **Improves hazard prediction** - through advanced modeling supported by a centralized national database.

- **Strengthens vulnerability analysis** - by including long-term projections such as climate change scenarios and socio-economic dynamics.


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The benefits of adopting a national approach are multi fold:

- **Consistency and comparability:** Assessments from different regions follow the same technical language and criteria, reducing discrepancies and improving coordination.
- **Comprehensive datasets:** Access to a centralized national repository of historical hazard data, bridge inventories, and climate projections enhances predictive modeling and scenario planning.
- **Strategic resource allocation:** Ensures that lifeline bridges—those critical for national highways, interstate trade routes, and defense logistics—are prioritized for retrofitting and resilience-building.
- **Cross-agency collaboration:** Promotes coordinated action among central and state governments, infrastructure agencies, disaster management authorities, and research institutions.
- **Long-term resilience:** Moves beyond short-term, local solutions to create a future-ready system capable of withstanding increasing hazard frequency and intensity.

Risks of Fragmented Approaches

Without a National RVA principle:

- RVA efforts remain fragmented and localized.
- Duplication of work and inconsistent standards become common.
- Critical bridge infrastructure may remain vulnerable to large-scale disruptions.
- Resource allocation becomes inefficient, leaving gaps in preparedness.

National RVA framework establishes coherence, fairness, and resilience at a systemic level. It safeguards not only day-to-day transportation but also national security, economic stability, and disaster response capabilities. Thus, the creation of a National RVA principle is not just a technical requirement but a strategic necessity for ensuring sustainable and resilient bridge infrastructure in the face of climate change and natural hazards[7].

Factors affecting risk and vulnerability of bridges

Risk and vulnerability evaluation of bridges is a multidimensional process shaped by three core elements: hazard, exposure, and vulnerability. These factors interact dynamically and determine the degree of risk faced by a bridge in different geographical, climatic, and structural contexts. Understanding each factor—and more importantly, their interplay—is essential for accurate Risk and Vulnerability Assessment [RVA] and effective decision-making.

1. Hazard

Hazard refers to the nature, type, frequency, and intensity of threatening events that can impact bridge infrastructure.

- **Climatic hazards:** floods, cyclones, droughts, extreme heat, and heavy rainfall.
- **Geophysical hazards:** earthquakes, landslides, and tsunamis.

Examples:

a) Coastal bridges are exposed to storm surges, cyclones, and saltwater corrosion.
b) Mountain bridges face risks from landslides, seismic activity, and flash floods.

- **Climate change impact:** Rising frequency and severity of hazards [example more intense rainfall, stronger storms] complicates long-term risk predictions.

The magnitude and recurrence of hazards dictate the stress levels imposed on bridges, requiring continuous monitoring and adaptation.

2. Exposure

Exposure represents the degree to which a bridge is located within a hazard-prone environment, as well as its functional significance.

Geographical exposure:

- Bridges in floodplains are highly exposed to seasonal flooding.
- Bridges near seismic fault lines face heightened earthquake risk.

Functional exposure:

- Some bridges serve as lifeline assets, enabling evacuation, relief operations, trade, and defense logistics during emergencies.
- Failure of such bridges has wider socio-economic and national security implications compared to smaller, less critical structures.

Exposure therefore combines both physical location and strategic importance, making it a key determinant in RVA prioritization.

3. Vulnerability

Vulnerability refers to the inherent capacity—or incapacity—of a bridge to withstand hazard impacts. It depends on both structural and non-structural attributes.

Structural attributes:

- Design type and construction standards.
- Age of the bridge and compliance with modern codes.
- Quality of construction materials.

Condition and maintenance:

- Inspection frequency and repair history.
- Deterioration from corrosion, fatigue, or thermal expansion.

Examples:

- Older bridges often lack resilience features present in modern designs.
- Newly built bridges may still be vulnerable if constructed with inferior materials or without site-specific hazard considerations.

Thus, vulnerability highlights the internal weaknesses that can amplify the impacts of external hazards.

4. Interplay of Hazard, Exposure, and Vulnerability

Risk is not determined by a single factor but emerges from the intersection of hazard, exposure, and vulnerability.

- A high-intensity hazard does not always mean high risk—if the bridge is outside the hazard zone or is structurally resilient.
- Conversely, even a moderate hazard can cause catastrophic failure if the bridge is both highly exposed and structurally weak.

Example:

- A medium-intensity flood may devastate an ageing bridge with eroded foundations in a river basin.
- A newly constructed, elevated bridge in the same location may withstand the same flood with minimal damage.

This interplay makes risk evaluation a case-specific, context-driven process rather than a universal calculation.

5. Dynamic Nature of Risk

Risk is not static; it evolves over time under the influence of both past experiences and future trends.

Historical data:

- Records of past hazards, damage patterns, and repair histories help identify vulnerability trends.

Future dynamics:

- Climate change is increasing the frequency, intensity, and unpredictability of hazards.

Advances in predictive modeling, climate projections, and resilient construction technologies must be incorporated into RVA.

A dynamic RVA approach ensures that bridge management strategies are continuously updated, proactive, and capable of addressing emerging risks effectively.

The risk and vulnerability of bridges is shaped by the complex interaction between hazards, exposure, and vulnerability. While hazards define the potential threats, exposure determines the bridge's likelihood of being impacted, and vulnerability dictates how severely it will be affected. Recognising the dynamic interplay of these factors—and updating assessments with both historical evidence and future projections—is critical for building resilient and sustainable bridge infrastructure[8,9].

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 useful but limited, makes National RVA framework essential for standardisation, integrated datasets, 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 lifeline bridges during disasters.

CHAPTER THREE:

IMPACT OF CLIMATE AND NATURAL HAZARDS ON BRIDGES

Bridges are long-life structures designed to perform safely and reliably over decades, often exceeding 50-100 years of service. Their ability to withstand extreme events is largely dictated by the bridge design principles, particularly the concept of design loads. However, the challenges posed by climate variability and natural hazards highlight the limitations of traditional design approaches, which have been strongly dependent on historical climate and hazard records.

1. Bridge Design Principles and the Concept of Design Loads

The design of bridges follows well-established engineering codes and standards [such as IRC, AASHTO, Eurocode], which prescribe the types and magnitudes of loads that must be considered. These are collectively referred to as design loads, and they form the foundation of structural safety.

Key Design Loads Considered in Bridge Engineering:

a) **Dead Loads:** The self-weight of the structure, including decks, girders, piers, and abutments.

b) **Live Loads:** Traffic loads due to vehicles, trains, or pedestrians. These are often prescribed by standard load models based on expected traffic patterns.

c) **Environmental Loads:** Forces from natural conditions such as wind, water flow, ice, snow, and temperature variations.

d) **Seismic Loads:** Earthquake-induced ground motion effects, which vary with seismic zoning.

e) **Special Loads:** Ship collisions, vehicular impacts, scour effects, and blast loads in sensitive regions.

These values are usually determined from historical climate and hazard data. For example, flood levels are calculated from past rainfall and river flow records, while seismic zones are based on recorded earthquake history[10].

2. Limitations in the Context of Climate Change

a. **Fixed Capacity:** Once designed, a bridge’s load-carrying capacity cannot be increased unless structural modifications or retrofitting are made.

b. **Historical Bias:** Design codes assume that future hazards will resemble past ones, which is increasingly unreliable as climate change alters the frequency and intensity of floods, cyclones, and heatwaves.

c. **Overlooked Cumulative Effects:** Multiple hazards acting together [example flooding, scour, and debris impact] often exceed what was originally accounted for in design.

3. Impacts of Climate and Natural Hazards

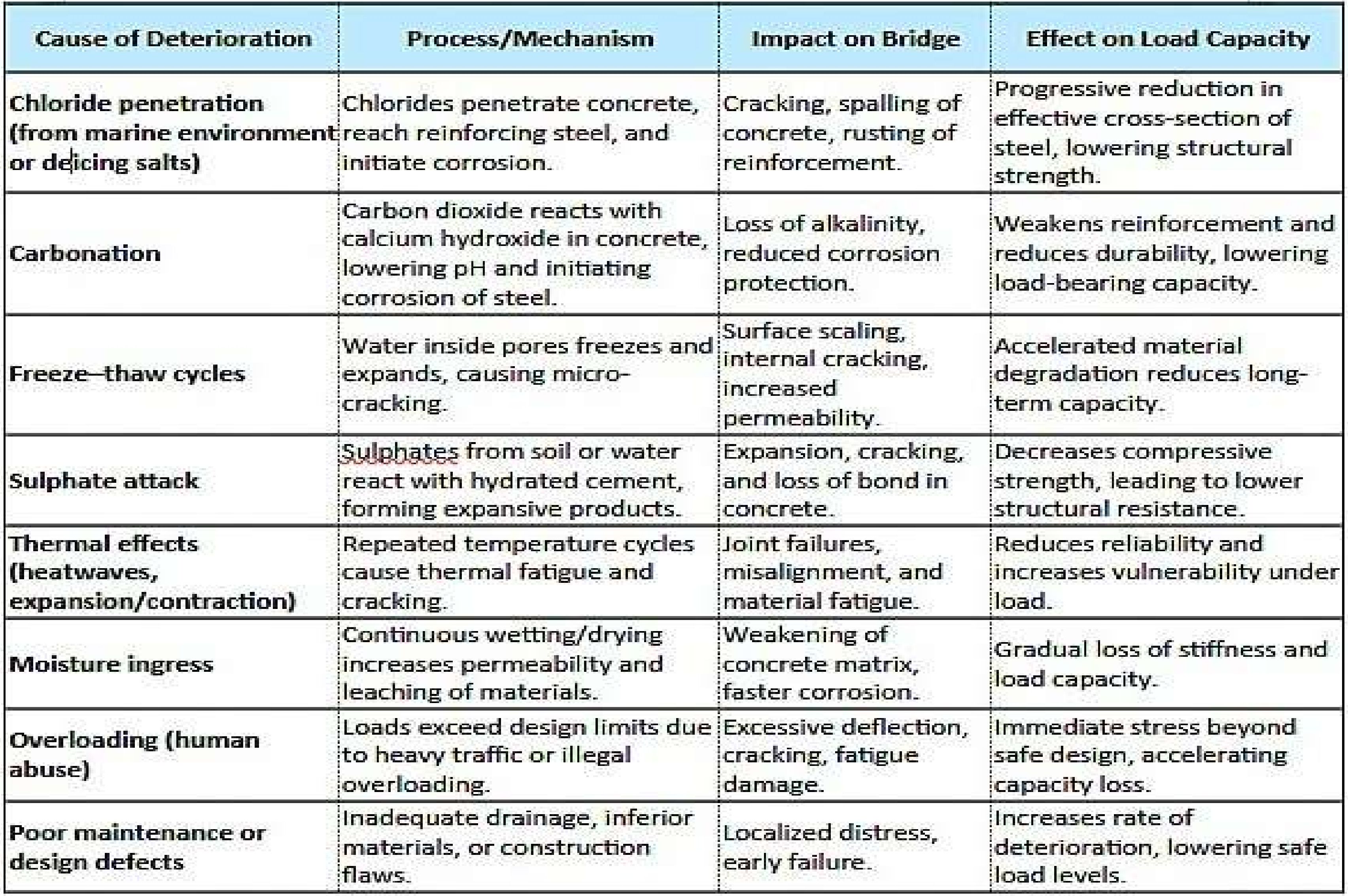
Risk is not determined by a single factor but rather emerges from the complex interplay of hazard, exposure, and vulnerability. A high-intensity hazard, such as a flood or earthquake, does not automatically translate into high risk if the bridge lies outside the hazard zone or possesses strong structural resilience. Conversely, even a moderate hazard can result in catastrophic consequences when a bridge is both highly exposed and structurally deficient. For instance, a medium-intensity flood may devastate an ageing bridge with eroded foundations located in a river basin, while a newly constructed, elevated bridge in the same area may withstand the same flood with minimal damage. This contrast illustrates that risk evaluation is not a universal calculation but a case-specific, context-driven process that must consider the unique interaction of environmental conditions, structural capacity, and geographical setting.

Bridge design principles rooted in historical hazard data provide a strong baseline but are increasingly inadequate under changing climatic conditions. Since design loads lock in a bridge's capacity, resilience can only be improved through modification, retrofitting, or forward-looking design approaches[11]. A shift towards climate-adaptive and future-oriented design is therefore essential for safeguarding bridge infrastructure.

Deterioration In Bridges [Process Which Leads To Reduction In Load Capacity]

Bridge deterioration is a progressive process that directly affects the structural integrity and load-carrying capacity of a bridge. From the moment a bridge is constructed, it begins to interact with its surrounding environment, and this interaction initiates mechanisms of deterioration. The primary causes of deterioration in concrete bridges can be broadly classified into climate-dependent factors, structural factors, and human-induced factors. Among these, climate-dependent causes are the most dominant and unavoidable.

In concrete bridges, deterioration often arises from environmental and climatic influences such as temperature variations, moisture ingress, freeze-thaw cycles, chloride penetration from de-icing salts or marine exposure, carbonation, sulphate attack, and corrosion of reinforcing steel. These processes are slow but relentless, and they begin almost immediately after the bridge is put into service. For example, repeated wetting and drying cycles accelerate the penetration of water and salts into concrete pores, leading to cracking and steel corrosion. Similarly, in hot climates, thermal expansion and contraction cause fatigue and micro-cracks, while in cold regions, freeze-thaw cycles damage the concrete matrix[12]. Since these factors are directly linked to the surrounding climate and natural conditions, they cannot be fully eliminated and instead must be managed through design, maintenance, and timely interventions.



Cause of Deterioration	Process/Mechanism	Impact on Bridge	Effect on Load Capacity
Chloride penetration (from marine environment or deicing salts)	Chlorides penetrate concrete, reach reinforcing steel, and initiate corrosion.	Cracking, spalling of concrete, rusting of reinforcement.	Progressive reduction in effective cross-section of steel, lowering structural strength.
Carbonation	Carbon dioxide reacts with calcium hydroxide in concrete, lowering pH and initiating corrosion of steel.	Loss of alkalinity, reduced corrosion protection.	Weakens reinforcement and reduces durability, lowering load-bearing capacity.
Freeze–thaw cycles	Water inside pores freezes and expands, causing micro-cracking.	Surface scaling, internal cracking, increased permeability.	Accelerated material degradation reduces long-term capacity.
Sulphate attack	Sulphates from soil or water react with hydrated cement, forming expansive products.	Expansion, cracking, and loss of bond in concrete.	Decreases compressive strength, leading to lower structural resistance.
Thermal effects (heatwaves, expansion/contraction)	Repeated temperature cycles cause thermal fatigue and cracking.	Joint failures, misalignment, and material fatigue.	Reduces reliability and increases vulnerability under load.
Moisture ingress	Continuous wetting/drying increases permeability and leaching of materials.	Weakening of concrete matrix, faster corrosion.	Gradual loss of stiffness and load capacity.
Overloading (human abuse)	Loads exceed design limits due to heavy traffic or illegal overloading.	Excessive deflection, cracking, fatigue damage.	Immediate stress beyond safe design, accelerating capacity loss.
Poor maintenance or design defects	Inadequate drainage, inferior materials, or construction flaws.	Localized distress, early failure.	Increases rate of deterioration, lowering safe load levels.

In contrast, some causes of deterioration are attributed to human abuse or design limitations—such as overloading beyond design limits, poor quality materials, inadequate maintenance, or construction defects. While these can be controlled through better planning and management, they account for only a fraction of the deterioration compared to the constant action of natural environmental forces.

The critical implication of these processes is that deterioration begins from day one of service and continues as the bridge ages, making older bridges significantly more prone to distress and failure. As deterioration progresses, the bridge's effective load-carrying capacity gradually reduces[13]. This reduction not only compromises the safety and durability of the structure but also leads to decreased performance, affecting serviceability, reliability, and resilience against hazards. Over time, if left unaddressed, deterioration can escalate to severe structural failures, causing disruptions to connectivity and posing risks to public safety.

Dynamism in natural hazard and climate change

The impacts of natural hazards and climate change on bridge infrastructure are becoming increasingly complex due to the dynamic changes in both frequency and severity of hazard occurrences. Events that were once considered "rare" [such as a 100-year flood] are now reoccurring within a decade, signaling a drastic shift in hazard return periods. This increase in frequency is often coupled with greater intensity, as evidenced by stronger cyclones, prolonged heatwaves, and more devastating floods. The dual effect of frequency and severity creates an unpredictable future scenario, making it extremely difficult for engineers and planners to forecast and prepare for forthcoming hazards.

This unpredictability complicates the exposure criterion in risk evaluations. Traditional risk assessment frameworks rely on predictable recurrence intervals and hazard magnitudes. However, with climate change driving non-linear, extreme fluctuations, exposure estimates become uncertain. Consequently, bridges that were once considered adequately safe may now fall into high-risk categories, not because of their inherent weakness, but because the hazard environment itself has become far more aggressive and less predictable[14].

Vulnerability of ageing deteriorated bridges

Ageing bridges present a unique challenge in risk and vulnerability evaluation because their performance decreases steadily over time while hazard intensity and frequency are increasing due to climate change. Unlike newly built bridges, which are designed to meet specific load and hazard criteria, older bridges experience material degradation and structural weakening that significantly reduce their load-carrying capacity. This reduction in capacity makes them more vulnerable when exposed to natural hazards such as floods, earthquakes, or cyclones.

Deterioration in bridges begins from the very first day after construction and progresses as the structure interacts with environmental and operational stressors. Common causes of deterioration include corrosion of reinforcement, cracking and spalling of concrete, fatigue in steel members, and scouring of foundations. While some of these causes can be attributed to human abuse [overloading, poor maintenance, use of inferior materials], the majority are climate-dependent, such as chloride ingress in coastal regions, freeze-thaw damage in colder zones, or scouring during floods. As deterioration advances, the bridge's ability to perform as originally designed steadily declines[15].

Key deterioration mechanisms include:

a) Corrosion of reinforcement caused by chloride attack or carbonation, leading to cracking and spalling of concrete.
b) Fatigue of steel components due to repetitive loading from traffic.
c) Foundation weakening from scouring, which reduces stability.
d) Concrete degradation from chemical reactions [sulphate attack, alkali-silica reaction] and environmental cycles.

The consequence of these processes is a progressive reduction in residual capacity. The original design capacity, which once guaranteed safety under prescribed loads and hazard conditions, no longer reflects the bridge's real-time strength. This means that a bridge which may have been safe decades ago could now be highly vulnerable, even under moderate hazards. For example, a medium-intensity flood might devastate an old bridge with eroded foundations, while a newer, elevated bridge in the same location may resist the same event with minimal damage.

- To address this, it becomes essential to:

a) Conduct detailed inspections and material testing to assess the present condition.
b) Quantify residual load-carrying capacity through analytical modeling and load testing.
c) Relate this reduced capacity to the expected hazard environment to predict vulnerability more accurately.

If such evaluations are not carried out, ageing bridges can quickly transition from being functional infrastructure to high-risk liabilities. They may fail during disaster events, endangering lives, disrupting connectivity, and weakening community resilience. Thus, vulnerability of ageing bridges is not a static measure but a dynamic outcome of how deterioration processes interact with evolving hazard conditions over time.

Key failure mechanisms during natural hazard occurrence

When natural hazards strike, the performance of a bridge depends on two key aspects: the nature of the hazard and the condition of the bridge at the time of impact. Failure is rarely caused by a single factor; instead, it results from a complex interaction between hazard forces and structural vulnerabilities. Broadly, the mechanisms of failure during natural hazard events can be categorized into three major groups: hydraulic, seismic, and wind/climatic.

A) Hydraulic Failures [Floods and Scouring]

Floods, storm surges, and river flow intensification exert significant hydraulic pressures on bridge substructures. One of the most critical concerns is scouring, the process where fast-moving water erodes the soil supporting bridge foundations.

- Foundation instability occurs when piers and abutments lose their bearing support.
- Once scouring reaches a critical depth, the foundation may tilt or fail abruptly, leading to sudden collapse.

- Floating debris during floods can exacerbate the impact by striking piers, increasing local stresses.

This failure mechanism is among the most common worldwide, as many bridges lie in floodplains and river basins[16].

B) Seismic Failures [Earthquakes and Ground Shaking]

Earthquakes subject bridges to dynamic and cyclic loading that challenges their ability to resist lateral and vertical forces.

a) Inadequate seismic detailing [common in older bridges] can cause brittle failures of joints and columns.
b) Soil liquefaction reduces the stability of foundations, causing piers to settle unevenly or collapse.
c) Lack of ductility and redundancy in design increases the chance of progressive failure.

Bridges built before the introduction of modern seismic codes are especially vulnerable, as they were not designed to withstand strong ground motions.

C) Wind and Climatic Failures [Cyclones, Storms, and Heatwaves]

Climatic extremes such as cyclones and heatwaves subject bridges to additional stressors.

a) High wind loads can trigger aerodynamic instability in long-span bridges, causing flutter, resonance, or vortex shedding.
b) Cyclones combine destructive wind speeds with storm surges, exposing bridges to simultaneous hydraulic and aerodynamic loads.
c) Extreme heat leads to expansion of structural members, thermal cracking, and in some cases, buckling of steel components.

These impacts often accelerate deterioration processes, making bridges weaker against future hazards.

D) Multi-Hazard Interaction

What makes natural hazards particularly dangerous is their tendency to act in combination. A single event often triggers multiple mechanisms simultaneously.

a) For instance, a cyclone can cause scouring at the foundations, impose high wind pressures on the superstructure, and accelerate corrosion through saltwater intrusion—all during the same event.
b) This multi-hazard interaction creates complex stress conditions that exceed the scope of single-hazard design approaches.

The failure mechanisms of bridges during natural hazards are highly dependent on hazard type but are amplified by deterioration, ageing, and design limitations. Understanding these mechanisms is essential for developing effective risk and vulnerability assessments, as it allows bridge managers to predict how different hazard forces interact with structural weaknesses and to prioritize mitigation strategies accordingly[17].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Bridges are designed for long service life for design loads, 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:

EVALUATION OF EXPOSURE CONDITION, DETERIORATION

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The evaluation of bridge vulnerability requires a systematic assessment of both external exposure conditions [environmental and hazard-related factors] and internal deterioration status [structural health of the bridge]. These two dimensions are interlinked: While exposure defines the level of hazard interaction, deterioration defines the bridge’s ability to withstand such interactions. Together, they determine the Balance Service Life [BSL], Available Balance Service Life [ABSL], and Minimum Service Life [MSL] of the structure.

What constitutes exposure condition

Exposure condition represents the degree to which a bridge is subjected to potential hazards during its service life. It is essentially defined by the historical narrative of hazard occurrence in the region where the bridge is located. Two critical parameters from past events—frequency and severity—form the foundation for understanding present-day exposure conditions.

- **Historical Frequency:** How often a hazard has occurred in the past provides a baseline estimate of the likelihood of its recurrence. For example, a river that floods once every three years indicates a higher exposure condition for nearby bridges compared to a river with flood records once every fifty years.

- **Historical Severity:** The intensity or magnitude of past hazards—such as peak flood levels, maximum recorded wind speeds, or earthquake magnitudes—helps define the stress levels a bridge has been [and may continue to be] exposed to. Severe past events increase the probability of significant exposure in the future.

However, exposure cannot be determined solely by static historical data. Dynamism in hazard frequency and severity must also be factored in. Climate change and environmental shifts are causing rare events [like “100-year floods” or “century storms”] to occur within decades or even shorter intervals. Similarly, hazards are becoming more intense, with higher peak flows, stronger winds, and more powerful seismic shocks being recorded[18].

To capture this dynamic element, past data from the immediate preceding years is crucial. Short-term historical trends reveal whether hazard frequency is increasing and whether severity is intensifying. This allows for adjustments in exposure condition that reflect present-day realities rather than outdated averages.

Exposure condition is not a static parameter but a time-sensitive assessment that combines the long-term historical record with short-term dynamic trends. By integrating both perspectives, engineers and planners can more accurately define the current exposure of a bridge to hazards and better anticipate the risks it will face in the near future[19].

Zoning of regions with common climate and NH characteristics, including identification of NH impacting the zone.

To standardise exposure evaluation and ensure consistency across different regions, it is essential to classify areas into zones that share similar climatic conditions and natural hazard profiles. Such zoning allows bridge managers and policymakers to apply uniform methodologies, prioritise interventions, and streamline resource allocation.

- **Climatic Zoning:**

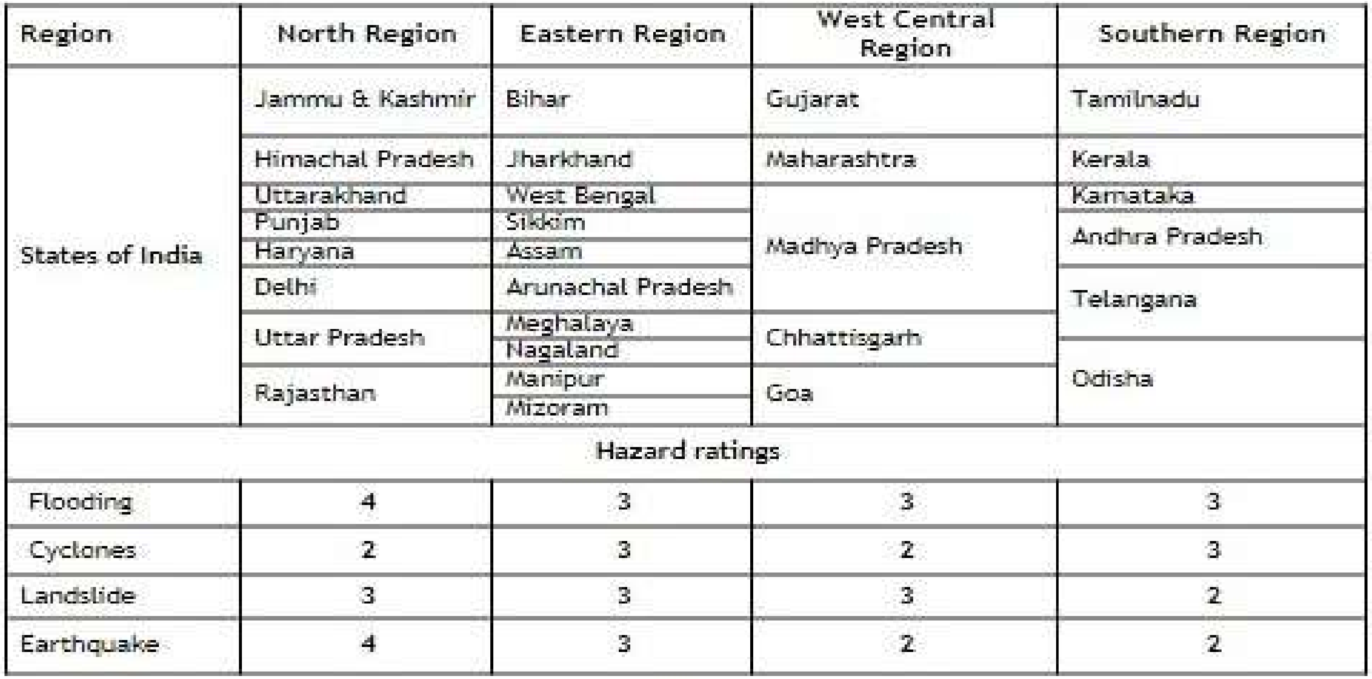
This involves categorising regions based on their prevailing climatic features—such as average and extreme temperature ranges, humidity levels, rainfall intensity, freeze-thaw cycles, and prevailing wind regimes. For instance, Himalayan regions would be marked by snow and freeze-thaw effects, while arid zones of Rajasthan would emphasis thermal stresses and sand abrasion.

- **Natural Hazard Zoning:**

In parallel, regions are mapped according to the dominant natural hazards that occur there. Examples include the Himalayan belt with its high seismic, coastal Odisha and Andhra Pradesh prone to recurrent cyclones, and the Ganga-Brahmaputra basin characterised by seasonal flooding. By defining zones around hazard types, bridges can be evaluated against the most probable hazard scenarios.

- **Hazard Impact Identification:**

Within each climatic or hazard zone, the type, frequency, and magnitude of likely impacts are identified. For example, in cyclone-prone areas, storm surge height, wind speed, and salt-laden air are critical factors, while in seismic zones, ground acceleration and liquefaction potential dominate[20]. This process ensures that bridges are not only categorised by location but also by the specific stresses they are most vulnerable to.



Region	North Region	Eastern Region	West Central Region	Southern Region
States of India	Jammu & Kashmir	Bihar	Gujarat	Tamilnadu
	Himachal Pradesh	Jharkhand	Maharashtra	Kerala
	Uttarakhand	West Bengal		Karnataka
	Punjab	Sikkim	Madhya Pradesh	Andhra Pradesh
	Haryana	Assam		
	Delhi	Arunachal Pradesh		Telangana
	Uttar Pradesh	Meghalaya	Chhattisgarh	
		Nagaland		
	Rajasthan	Manipur	Goa	Odisha
		Mizoram		
Hazard ratings				
Flooding	4	3	3	3
Cyclones	2	3	2	3
Landslide	3	3	3	2
Earthquake	4	3	2	2

Example for zoning applied to INDIA

By adopting a zonal approach, Risk and Vulnerability Assessments [RVA] become more targeted and efficient. It enables uniform policy frameworks to be applied across regions with similar hazard environments, while also reducing discrepancies in evaluation standards between states or agencies.

The exposure of a bridge to hazards is not defined only by its immediate physical environment, but also by the larger geographical context and the role it plays in human systems. This makes it essential to evaluate exposure through three complementary lenses:

Geospatial Boundaries

Definition: Geospatial boundaries refer to both physical features [rivers, coasts, mountains, floodplains, seismic fault lines] and administrative divisions [district, state, national, or even international borders].

Why is it Important ?: Bridges often span across or connect these boundaries, making them critical points of exposure. For example:

- A bridge on a river that marks a state border may be under the administrative control of two governments, complicating hazard management.

- A bridge in a coastal cyclone-prone zone [example: Odisha] will face compound risks from storm surges, saline corrosion, and high winds simultaneously.

Implication: Exposure assessments must capture how hazards and boundaries overlap. A single bridge may sit at the intersection of multiple risk zones [example flood + cyclone + saline environment].

Interconnectivity

Definition: Interconnectivity captures the bridge’s role within the transportation and economic network it belongs to.

Why is it Important?: Some bridges connect rural communities, while others link national highways, interstate trade corridors, ports, or rail lines. Their failure has very different levels of impact.

Examples:

A bridge on the Golden Quadrilateral Highway in India carries heavy truck traffic across states—failure would disrupt trade and logistics nationwide.

A rural bridge in a village may only affect local commuting, though it may still be vital for emergency response in that community.

Implication: Bridges with high network centrality [key nodes in the transport grid] have higher exposure impact, because their failure can cascade into regional or national disruption.

Socio-Economic Considerations

Definition: This refers to the functional and strategic importance of the bridge for society, economy, and governance.
Why Important: A bridge may have modest physical exposure but still be “high exposure” due to its socio-economic role.

Examples:

Trade & Supply Chains: Bridges that connect industrial hubs, ports, or border trade routes are economic lifelines.

Emergency Access: Bridges that provide access to hospitals, evacuation routes during floods, or disaster-relief corridors gain critical importance.

Strategic/Military Role: Bridges near borders or defense installations [example in Arunachal Pradesh or Ladakh] are indispensable for national security, making them high-priority in exposure assessments.

Implication: Socio-economic value amplifies the perceived exposure. Even a well-maintained, hazard-resilient bridge can be classified as high-exposure if it is functionally irreplaceable.

When evaluating exposure, spatial location sets the physical hazard context, inter-connectivity defines the systemic importance, and socioeconomic role elevates the bridge's criticality. Together, these considerations ensure that exposure assessment captures not only the probability of hazard impact but also the scale of consequences if the bridge fails[21].

Evaluation of deterioration status of bridge.

Once the exposure condition of a bridge has been established, the next essential step is to determine its deterioration status. Deterioration represents the internal resistance of the bridge to withstand applied loads and hazards. Unlike exposure, which is external, deterioration reflects the inherent structural health of the bridge.

c) **Key Factors in Deterioration:**

Material Degradation

- **Corrosion of Reinforcement:** Chloride ingress, carbonation, and moisture accelerate corrosion of embedded steel. This weakens reinforcement and causes cracking in concrete.
- **Steel Fatigue:** Repeated loading from traffic and vibrations leads to microscopic cracks and eventual fatigue failure in steel girders or cables.
- **Alkali-Silica Reaction [ASR]:** A chemical reaction in concrete that causes expansion, cracking, and long-term loss of strength.

Structural Distress:

- **Cracking and Spalling:** Visible cracks, delamination, and falling concrete layers reduce effective cross-sectional strength.
- **Deformation:** Bending, tilting, or sagging in girders and decks indicates compromised stiffness.
- **Settlement or Scouring:** Foundation movement due to soil erosion or poor compaction reduces stability.

Ageing Effects:

Over decades, time-dependent wear and tear gradually reduces a bridge's load-carrying capacity, even if no major hazard occurs.

Materials lose ductility, joints loosen, and protective coatings deteriorate, making older bridges naturally more vulnerable.

- **Maintenance Records:**

The history of inspections, repairs, or retrofitting is critical.

A bridge with timely interventions may perform well despite age, while one with poor maintenance deteriorates rapidly.

- **Evaluation Techniques:**

Visual Inspection: Basic but useful for identifying cracks, corrosion, or settlement.

Non-Destructive Testing [NDT]: Methods like ultrasonic pulse velocity, rebound hammer tests, and ground-penetrating radar provide quantitative health insights.

Structural Health Monitoring [SHM]: Continuous monitoring using sensors [strain gauges, accelerometers] helps track deterioration in real-time.

Impact of deterioration status on BSL, ABSL and MSL

The evaluation of deterioration is not just diagnostic—it directly affects how long the bridge can continue to function safely. This is quantified using service life parameters:

- **Balance Service Life [BSL]:**

Balance Service Life [BSL] refers to the remaining years a bridge can continue to function safely under its current condition, assuming no major repairs or strengthening are carried out. It reflects the bridge's ability to perform its intended role despite deterioration.

For example, if a bridge was originally designed for a 100-year lifespan, but deterioration such as corrosion, cracking, or scouring has weakened its structure, the effective BSL may drop to only 15-20 years. This shortened timeline highlights the urgency of intervention. BSL is highly sensitive to hazard exposure. Frequent floods, earthquakes, or cyclones accelerate deterioration, further reducing the remaining service life. Thus, BSL provides a baseline measure of how soon a bridge may become unsafe if left unmaintained.

- **Absolute Balance Service Life [ABSL]:**

Absolute Balance Service Life [ABSL] refers to the service life of a bridge once all possible interventions—such as strengthening, retrofitting, or advanced maintenance—are taken into account. It provides a more practical estimate compared to the theoretical design life or the current balance service life.

For example, an ageing bridge with only 20 years of balance service life left may undergo retrofitting using seismic dampers, foundation strengthening, or corrosion protection techniques. With these interventions, the bridge's service life could be extended to 40 years. Thus, ABSL represents the realistic and achievable lifespan of a bridge. It balances the impact of deterioration with the effectiveness of repair and maintenance measures, giving decision-makers a clearer view of how long the bridge can continue to serve safely and efficiently.

- **Median Service Life [MSL]:**

Median Service Life [MSL] represents the critical safety threshold of a bridge. It marks the stage beyond which the structure can no longer be considered safe or serviceable for public use.

Severe deterioration factors—such as foundation scouring, advanced corrosion of girders, or extensive structural cracking—can accelerate the approach to MSL. This risk is even greater in hazard-prone regions, where frequent floods, earthquakes, or cyclones place additional stress on already weakened structures. Once a bridge reaches its MSL, routine maintenance or minor repairs are no longer sufficient. At this point, only complete replacement or major reconstruction can restore the required safety and serviceability standards.

Deterioration evaluation provides the internal health picture of a bridge. Its impact is translated into BSL [remaining time], ABSL [extendable time with intervention], and MSL [absolute safety limit]. This framework ensures decision-makers know not only the current health but also how much longer the bridge can reliably serve before becoming a liability[22].

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 make extreme events more frequent and intense. To standardize assessments, zones are defined by climate and hazard profiles, with exposure 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 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:

RISK AND VULNERABILITY ANALYSIS

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Definition of risk and vulnerability focus [time focus, expectations, regulatory needs, criticality with respect to rescue and relief operations.

Risk and vulnerability analysis is a critical step in understanding the safety, functionality, and resilience of bridge infrastructure under changing hazard conditions. While risk represents the probability of loss or failure when a hazard interacts with a bridge, vulnerability captures the inherent weaknesses that make a structure more susceptible to damage. The focus of this analysis is both time-dependent—reflecting how risks evolve with ageing, deterioration, and shifting climate patterns—and expectation-driven. Stakeholders anticipate safe, uninterrupted service even during extreme events. From a regulatory standpoint, such assessments are necessary to align with safety codes, disaster management policies, and long-term infrastructure planning. Equally important is the criticality of bridges during rescue and relief operations: failures along key corridors can delay emergency response, disrupt evacuation, and isolate affected communities[23]. Thus, risk and vulnerability analysis provides a structured approach to anticipate failures, prioritize interventions, and ensure that critical transport lifelines remain functional during disasters.

- **Risk:**

Risk is the probability of damage, disruption, or collapse of a bridge when exposed to natural or man-made hazards [floods, earthquakes, landslides, heavy traffic loads, etc.]. For bridges, risk is not only about structural failure but also about the broader impact on connectivity, such as cutting off access to towns, villages, and critical facilities.

- **Vulnerability:**

Vulnerability refers to the inherent weaknesses of a bridge that make it more susceptible to hazards. This includes ageing materials, design limitations, lack of maintenance, poor construction quality, or exposure to high-intensity events [like rivers prone to flash floods]. A vulnerable bridge may not fail immediately but will have reduced service life and higher chances of functional disruption.

Together, risk and vulnerability define not only the probability of damage but also the severity of disruption caused if a bridge fails. In disaster management terms, bridges with high vulnerability and high exposure are the most critical to monitor, as their failure can directly hinder rescue and relief operations.

Focus Dimensions in Risk and Vulnerability

- **Time Focus**

Bridges deteriorate with age, and hazard conditions intensify with climate change. Risk is therefore time-dependent. A bridge safe today may become unsafe in the next decade without maintenance, monitoring, or upgrades.

- **Expectations**

Stakeholders—including the public, governments, and emergency agencies—expect uninterrupted bridge performance. Any disruption, even partial, is unacceptable during emergencies when connectivity is most needed.

- **Regulatory Needs**

Risk and vulnerability analysis must align with codes, safety standards, and disaster management guidelines. For example, regulatory frameworks may require hazard zoning, periodic inspections, or mandatory retrofitting of critical bridges.

Criticality in Rescue and Relief Operations

The most crucial focus is identifying bridges that serve as lifelines during disasters. A bridge connecting highways to hospitals, airports, or remote villages is not just infrastructure—it is a critical asset for evacuation, relief supply movement, and emergency services. If such a bridge fails, entire regions can be isolated, delaying rescue and increasing human and economic losses.

Concept of Critical Bridge Location in Rescue and Relief

Bridges are not uniformly important; their location determines their criticality. A bridge that provides the only access route to a flood-prone valley, a hilly settlement, or a cyclone-affected coastal area is far more critical than one with alternate routes nearby. In disaster response, time is life, and the ability to move relief materials, medical aid, and rescue teams depends on whether such critical bridges remain functional. Therefore, the identification and maintenance of critical bridges and the roads they connect to must be prioritised. These bridges form the backbone of regional connectivity during crises, and their risk and vulnerability status should guide government action plans, resource allocation, and emergency preparedness.

8) Availability of historical climate data and establishing standards.

The foundation of any risk and vulnerability assessment of bridges lies in the availability of authentic and reliable historical climate and hazard data. This data provides the baseline for identifying hazard frequencies, intensities, and long-term patterns, which in turn help in establishing scientific standards for exposure assessment. Without such records, hazard evaluation risks being arbitrary and non-representative of the actual conditions.

How Historical Data Can Be Collected

Historical climate and hazard data can be sourced from multiple levels—national, international, and regional. The collection methods include:

- **Government Meteorological Records:** Long-term datasets on rainfall, temperature, wind, humidity, and extreme events.
- **Hydrological and River Basin Data:** Records of river discharge, peak flood levels, and droughts from water resource departments.
- **Seismic and Geological Databases:** Information on earthquakes, soil liquefaction, and landslides from geological surveys.

Major Authentic Sources of Historical Data

Reliable historical climate and hazard data is available through multiple national and international agencies that specialise in weather monitoring, disaster management, and earth sciences. In India, the India Meteorological Department [IMD] provides long-term records on rainfall, temperature, cyclones, and other extreme weather events, making it one of the most critical repositories for climate-related datasets. Similarly, the Central Water Commission [CWC] maintains detailed information on floods, river discharge patterns, and dam records, which are essential for understanding hydrological hazards and their impact on bridge infrastructure.

The National Remote Sensing Centre [NRSC] under ISRO contributes valuable satellite-based data for flood inundation mapping, drought monitoring, and hazard zone identification. Complementing this, the National Disaster Management Authority [NDMA] compiles official disaster reports, hazard profiles, and risk assessments that directly support vulnerability evaluations at regional and national levels. The Geological Survey of India [GSI] provides hazard-specific data related to seismic activity, landslides, and soil or rock conditions, which are crucial for bridges located in geologically sensitive zones.

At the policy and research level, the Ministry of Earth Sciences [MoES] delivers datasets on cyclones, oceanographic conditions, and climate change projections, helping in long-term hazard forecasting. On the global scale, organisations such as the World Meteorological Organisation [WMO] provide standardised climate datasets and disaster statistics for comparative and integrative studies. Additionally, international agencies like NASA Earth Data offer satellite-based global datasets on rainfall, wind, and temperature, while the National Oceanic and Atmospheric Administration [NOAA] through its National Centres for Environmental Information [NCEI] maintains comprehensive archives on storms, cyclones, and long-term climate records.

Together, these sources create a comprehensive ecosystem of data, combining ground-based observations, satellite monitoring, and historical records. This allows engineers, planners, and policymakers to establish credible standards for exposure evaluation, hazard zoning, and resilience planning of bridges across diverse geographic and climatic conditions.

How to Decide Essential Values for Analysis

From historical datasets, the following essential parameters are extracted for bridge risk and vulnerability assessment:

- **Frequency of Events:** example: how often floods or cyclones have occurred in the last 50–100 years.
- **Severity/Intensity of Events:** peak flood discharge, maximum wind speed, earthquake magnitude.
- **Return Periods:** recurrence intervals such as “50-year flood” or “100-year storm” values used in design standards.
- **Duration of Hazards:** length of flooding, drought spells, or storm impacts.
- **Trend Analysis:** detecting if hazards are becoming more frequent or intense due to climate change.
- **Regional Standards:** converting raw data into zoning standards [example seismic zone maps, wind velocity zones, flood-prone districts].

By combining long-term averages [historical frequency/severity] with recent short-term trends [climate variability, intensification], engineers can set exposure benchmarks. These benchmarks are then integrated into bridge design, maintenance planning, and prioritisation of critical roads for disaster resilience.

Definition of Risk and its dependence on Vulnerability and exposure.

In the context of bridges, risk is defined as the probability of adverse consequences—such as partial damage, total collapse, or functional disruption—arising from the interaction between external hazards and the bridge’s structural condition. Risk is not a standalone parameter; rather, it is determined by two interdependent components: exposure and vulnerability.

f)
g)

- Exposure refers to the degree to which a bridge is subjected to natural hazards or environmental stressors. This includes its geographical location [example flood-prone basin, cyclone coast, or seismic belt], climatic conditions [rainfall, wind, freeze-thaw cycles], and socio-functional setting [whether it lies on a critical highway or a local rural road].

- Vulnerability, on the other hand, reflects the internal condition of the bridge—its material durability, structural health, ageing, and maintenance record—which determines how well it can withstand external hazard forces.

Thus,

risk = f [exposure × vulnerability].

Even if exposure is high, a bridge in good structural health with strong resilience measures may still have moderate risk. Conversely, a deteriorated bridge in a low-exposure area may still be at risk due to poor inherent resistance. The correct assessment of both components is therefore essential for reliable risk evaluation.

Consideration to define RVA methodology.

The RVA methodology provides a systematic framework to quantify and interpret the risk associated with bridges. Several considerations guide its formulation:

- **Time Focus -** RVA must account for both short-term and long-term risks. Short-term focuses on immediate hazard events [like monsoon floods], while long-term covers trends such as climate change and ageing deterioration.
- **Hazard Identification -** The type, frequency, and severity of hazards [floods, earthquakes, cyclones, landslides] in the bridge’s zone are the starting point for RVA.
- **Exposure Mapping -** Defining climatic zones, hazard-prone regions, and socio-economic dependencies of bridges.
- **Vulnerability Assessment -** Evaluating deterioration status, material quality, design standards, and past maintenance records.
- **Critical Functionality -** Recognizing bridges that are lifelines during rescue and relief operations, trade flows, and military logistics. These require priority evaluation.
- **Data Integration -** Combining historical records, satellite monitoring, and real-time inspection data to ensure RVA captures both static and dynamic conditions.

By combining these considerations, RVA transforms into a decision-making tool that not only measures present-day risk but also supports prioritisation of bridges for retrofitting, monitoring, or replacement.

Evaluation of Vulnerability and define critical routes

The evaluation of vulnerability is a core pillar in bridge risk assessment because it determines how well [or poorly] a bridge can withstand external hazard forces. Vulnerability is not a single parameter but a composite measure of structural health, ageing, design quality, and maintenance practices, combined with the bridge’s role in the transport network.

Structural and Material Vulnerability

- **Material Degradation:** Reinforcement corrosion, fatigue of steel, alkali-silica reaction, and concrete spalling reduce strength.
- **Structural Distress:** Settlement of foundations, scouring, excessive

vibrations, or visible cracking can critically impair resilience.
- **Design Deficiencies: Older bridges often lack seismic detailing, ductile design, or provisions against modern traffic loads, making them inherently vulnerable.**
- **Ageing: Time-dependent deterioration [loosening of joints, weakening of protective coatings] reduces the bridge's margin of safety even without a major hazard event.**
- **Maintenance Gaps:** Inadequate or delayed interventions accelerate deterioration, pushing bridges into higher vulnerability categories.

Functional Vulnerability

Vulnerability also depends on the functional importance of a bridge:
- **A rural bridge with limited traffic may be vulnerable structurally but its socio-economic impact of failure is localised.**
- **A bridge on a national highway or evacuation corridor carries far higher functional vulnerability since its failure disrupts trade, rescue** operations, and regional connectivity.

Defining Critical Routes

Critical routes are the transportation lifelines that form the backbone of regional and national movement. Bridges located on these routes are considered high-priority assets. Identifying critical routes involves:

- **Connectivity Analysis:** Roads that connect multiple districts, interstate highways, or corridors linking economic hubs.
- **Rescue and Relief Relevance:** Roads designated as primary evacuation routes during floods, earthquakes, or cyclones. Bridges here must remain serviceable during disasters.
- **Network Centrality:** Roads and bridges that act as choke-points failure of one asset disrupts an entire network.
- **Strategic/Military Importance:** In border states [example J&K, Arunachal Pradesh, Ladakh], critical routes have a defence role in addition to civilian connectivity.

This section shows that vulnerability is not just about physical condition but also about functional role. Highlighting critical routes strengthens the disaster risk reduction [DRR] perspective, aligning the paper with national resilience priorities. It helps justify why certain bridges demand continuous monitoring, priority funding, and preventive maintenance over others.

Evaluation of Risk

Evaluation of Risk represents the final step in bridge risk assessment, where the combined effects of exposure to external hazards and the inherent vulnerability of a bridge are analyzed to determine the likelihood and severity of potential failure. Risk can be understood as a function of Exposure × Vulnerability, where different combinations produce varying outcomes. For instance, bridges with both high exposure and high vulnerability face extremely high risk, while even those with low exposure but high vulnerability remain unsafe due to internal weaknesses. Conversely, well-designed and well-maintained bridges with low exposure are placed in the safest category.

Risk is multi-dimensional and extends beyond the structural condition of a bridge. It encompasses structural risk, such as the probability of collapse; functional risk, including traffic disruption and connectivity loss; socio-economic risk, which captures impacts on trade, industries, and local communities; and disaster-response risk, reflecting the consequences for rescue and relief operations during emergencies. Evaluating risk, therefore, requires both qualitative and quantitative methods, ranging from expert-based risk rankings and hazard maps to probabilistic modeling and scenario-based simulations of extreme events.

The ultimate purpose of risk evaluation is to enable effective decision-making and prioritisation. Bridges on critical routes with high risk demand urgent retrofitting or replacement, while those with moderate risk can be addressed through targeted maintenance. Low-risk bridges require regular monitoring to prevent future escalation. By applying this comprehensive evaluation framework, the process directly supports policy outcomes such as fund allocation, maintenance scheduling, and disaster risk reduction [DRR] strategies. Importantly, it emphasizes that bridge risk assessment must account not only for physical safety but also for the wider societal, economic, and disaster management implications of potential failure.

Understanding risk and vulnerability assessment concepts

The Risk and Vulnerability Assessment [RVA] helps municipalities evaluate climate-related risks by analysing hazards, exposure, vulnerabilities, and adaptive capacity. A clear understanding of key terms—such as hazard, exposure, vulnerability, impact, risk, adaptive capacity, and response measures—is essential for accurate assessments and collaboration.

The objectives of RVA are to identify climate hazards [example floods, heatwaves, sea-level rise], assess vulnerable populations, sectors, and assets, and determine adaptive capacity. Its expected outcomes include risk profiles, vulnerability maps, impact assessments, and evaluations of resilience, forming the basis for targeted climate adaptation planning.

Developing an RVA faces challenges, including data gaps, uncertainty in climate projections, and the complexity of integrating natural and socio-economic factors. Expert judgement, stakeholder engagement, and continuous monitoring are vital to address these limitations.

The process is guided by principles of equity and inclusive, quality and transparency, and a precautionary approach that accounts for uncertainty and prioritises “low-regret” actions.

Given the diversity of methods, the EU promotes a common RVA approach, harmonised through the Global Covenant of Mayors’ Common Reporting Framework [CRF]. This standardisation improves comparability, efficiency, collaboration, data integration, capacity building, informed decision-making, public engagement, and scalability across municipalities and regions.

The Risk and Vulnerability Assessment [RVA] process is a structured approach that enables municipalities to identify climate hazards, assess the exposure of populations, assets, and infrastructure, evaluate vulnerabilities and adaptive capacity, and prioritise risks for targeted adaptation planning. Its purpose is to develop risk profiles, vulnerability maps, and impact assessments that form the basis for informed decision-making. The process begins with identifying past and future hazards and continues with evaluating the exposure of people, ecosystems, and infrastructure to these hazards. Vulnerability is then assessed by examining the ability of systems and communities to withstand, adapt to, and recover from adverse events. Adaptive capacity is equally important, as it measures the institutional, financial, and social resources available to manage risks. These steps together define the level of risk, which is a function of hazard, exposure, and vulnerability, and this risk is analysed in structural, functional, socio-economic, and disaster-response terms. The success of an RVA depends on the establishment of a multidisciplinary team that draws on expertise from sectors such as health, transport, water, agriculture, finance, and emergency services, coordinated by an Adaptation Officer to ensure accountability and continuity. Stakeholder engagement is integral throughout the process to ensure inclusive, build trust, and integrate local knowledge.

By using tools such as hazard maps, exposure maps, vulnerability indicators, and geospatial modelling, municipalities can identify hotspots and critical infrastructure under threat, particularly roads and bridges that serve as lifelines during rescue and relief operations[24].

Risk evaluation is the synthesis stage where hazards, exposure, and vulnerability are combined to determine the likelihood and consequences of adverse outcomes. This includes structural risks like collapse or failure, functional risks like connectivity disruption, socio-economic risks such as economic losses, and disaster-response risks that may hinder relief operations.

Adaptation goals must be specific, measurable, achievable, relevant, and time-bound [SMART], ensuring that strategies are practical and effective.

Proper documentation, reporting, and communication of the RVA outcomes are essential for transparency, accountability, and community engagement. By embedding these practices, one can prioritise retrofitting and maintenance of critical infrastructure and strengthen resilience, ensure continuity of services, even against future climate risks.

Risk and Vulnerability Analysis (RVA) the foundation for assessing the resilience and reliability of bridges 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. 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 synthesizes these factors to categorize 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:

RISK AND VULNERABILITY ANALYSIS LEADING TO PRIORITISATION

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Evaluation of Vulnerability and define critical routes

The Risk and Vulnerability Assessment [RVA] serves as the cornerstone for making informed, evidence-based decisions in disaster risk reduction and infrastructure management. RVA results in definition of identification of criticality that the bridge is exposed to for that type of natural hazard. When all the bridges are analysed under RVA, the set of bridges that are critical for the type of hazard and the severity of hazard event is defined. This enables the authority to choose the best route to take during rescue and relief operation post occurrence of the event. Alternatively the worst route also get identified by this method.

In the context of bridges and critical road networks, RVA provides a structured methodology to link hazard identification, exposure assessment, and vulnerability evaluation with practical outcomes for prioritisation. By systematically analysing the interaction between external hazards and the internal condition of infrastructure, the process identifies which bridges and routes face the greatest risk and, therefore, demand immediate intervention.

This chapter emphasises how RVA transforms data into actionable priorities. It moves beyond theoretical assessment to highlight which structures are most critical for connectivity, socio-economic stability, and rescue and relief operations during disasters. Prioritisation, in this sense, is not merely technical but strategic—ensuring that limited resources are channelled toward maintaining and strengthening infrastructure that has the highest functional and societal importance.

Through this framework, the chapter illustrates how hazards, vulnerabilities, and adaptive capacities converge into a comprehensive risk profile. It demonstrates the transition from risk evaluation to decision-making, where bridges and roads are categorised into high, medium, or low priority[25]. Ultimately, this approach provides disaster management authorities and policymakers with a clear roadmap to safeguard lifeline infrastructure, enhance community resilience, and align with broader climate adaptation and disaster preparedness goals.

Define criticality conditions and risk indicators and matrix

Defining criticality conditions, risk indicators, and the risk matrix is a central step in translating the results of a Risk and Vulnerability Assessment [RVA] into practical decision-making tools. Criticality conditions describe the circumstances under which a bridge or road segment becomes vital for society, economy, or emergency response.

These conditions take into account the bridge's structural health, its role within the transport network, its socio-economic significance, and its indispensability during disaster events such as floods, earthquakes, or cyclones. A bridge may not be structurally deficient, but if it is the only link to a hospital, an industrial hub, or a disaster relief corridor, it automatically becomes critical. Similarly, bridges located on national highways, border roads, or trade routes carry far higher criticality than rural connectors, even if the latter are important locally.

Risk indicators are the measurable parameters used to evaluate these criticality conditions in a systematic and consistent way. They may include exposure to hazards [example frequency of flooding, seismic intensity zone], structural vulnerability [example age, material deterioration, design standards], functional dependence [example daily traffic volume, absence of alternative routes], and socio-economic relevance [example link to markets, ports, or emergency facilities]. Additional indicators can highlight the bridge's importance in rescue and relief operations, such as whether it forms part of an evacuation route, a supply chain for relief goods, or access to military and disaster management bases. By quantifying these diverse aspects, risk indicators transform qualitative judgements into comparable and transparent measures.

The Risk Indicator Matrix brings these indicators together into a structured evaluation framework. It cross-references the levels of exposure, vulnerability, and criticality with the potential consequences of failure, producing a clear picture of overall risk. For example, a bridge with high hazard exposure, high structural vulnerability, and high socio-economic importance would be placed in the extreme-risk category, demanding immediate action. Conversely, a bridge with low exposure, low vulnerability, and limited socio-economic impact may be placed in the low-risk category, requiring only routine monitoring. The matrix thus becomes a decision-support tool that enables engineers, planners, and disaster management authorities to prioritise interventions based not just on technical deterioration but on wider societal needs.

By evolving this matrix, we ensure that bridge risk assessments are not only technical evaluations but also holistic frameworks that reflect the true criticality of infrastructure in maintaining resilience and continuity during both normal conditions and emergency situations[26]. It provides a rational, transparent, and scale-able method for defining which bridges must be strengthened, maintained, or replaced first, aligning engineering practice with disaster preparedness and community safety objectives.

How It Works

Each bridge is evaluated against the five criteria and given a score between 1 and 5. The Risk score determines the risk class of the bridge. This matrix thus integrates hazard, vulnerability, and socio-economic relevance into one clear, practical decision-making tool for prioritising bridges under Disaster Risk Reduction [DRR] frameworks.

Sample Risk Indicator Matrix for Bridges

Criteria	Indicator	Scoring Scale (1-5)	Remarks
Hazard Exposure	Flood frequency, seismic zone, cyclone risk	1 = Very Low 5 = Very High	Based on historical hazard maps & climate data
Structural Vulnerability	Age, material condition, design compliance	1 = Excellent 5 = Very Poor	Inspection reports & load testing results
Functional Importance	Traffic volume, connectivity to key routes	1 = Minimal 5 = Critical	Traffic census & road hierarchy
Socio-Economic Importance	Access to markets, industries, hospitals	1 = Low 5 = High	Regional economic studies
Relief & Rescue Criticality	Role in evacuation, access to shelters, supply chains	1 = Not Relevant 5 = Lifeline Route	Disaster management and evacuation maps

<table>
<tr><th colspan="5">RISK SCORE TO WEIGHT-AGE ASSIGNMENT</th></tr>
<tr><th rowspan="2">HAZARD SCORE & PERCENTAGE</th><th colspan="4">PERCENTAGE FOR OTHER CRITERIA BASED ON HAZARD EXPOSURE</th></tr>
<tr><th>Structural Vulnerability</th><th>Functional Importance</th><th>Socio-Economic Importance</th><th>Relief & Rescue Criticality</th></tr>
<tr><td>1 [20]</td><td>20</td><td>100</td><td>100</td><td>20</td></tr>
<tr><td>2 [40]</td><td>40</td><td>80</td><td>80</td><td>40</td></tr>
<tr><td>3 [60]</td><td>50</td><td>50</td><td>50</td><td>50</td></tr>
<tr><td>4 [80]</td><td>90</td><td>20</td><td>20</td><td>90</td></tr>
<tr><td>5 [100]</td><td>125</td><td>15</td><td>15</td><td>125</td></tr>
</table>

Composite Risk Scoring

- **Low Risk:** Routine monitoring sufficient.
- **Moderate Risk:** Needs preventive maintenance/strengthening.
- **High Risk:** Prioritised for retrofitting or major strengthening.
- **Extreme Risk:** Immediate intervention or **replacement** required.

How to make operational the above in an RVA: a simple, repeatable procedure using the Risk Indicator Matrix:

The following procedural workflow shows how to convert inspection and hazard data into a decision on whether a bridge requires rehabilitation, retrofit or replacement using the Risk Indicator Matrix as the core tool.

Step 1 - Gather inputs:

- Hazard data [historical frequency, recent trend indicators, projected changes].

- Bridge inventory and functional data [location, traffic, network role].

- Deterioration evidence [visual inspection, NDT, SHM metrics, maintenance history].

- Socio-economic importance [connectivity to hospitals, supply chains, defence related criticality].

- Emergency criticality [role in rescue & relief routes].

Step 2 - Define indicators and normalise

- Select indicators for each matrix dimension and convert them to a common scoring scale [example 1-5].

- Likelihood [hazard frequency / projections]

- Structural vulnerability [deterioration score from inspection/ NDT]: 1 = excellent, 5 = critical.

- Functional importance [network centrality, traffic volume]

- Socio-economic consequences:
  1 = low, 5 = catastrophic.

- Relief & rescue criticality:
  1 = negligible, 5 = essential lifeline route.

Step 3 - Weight the indicators

Assign weights that reflect local priorities. Here the Hazard criteria is taken as the base and all weights are assigned with respect to the Hazard. So these weights will deviate as per the Hazard score. For every hazard score a percentage is assigned. Example Hazard score of 1 is assigned percentage of 20 and culminating with assignment of 100 percent for score of 5.
Similar percentages are assigned to other four parameters.

Step 4 - Compute composite risk / impact score

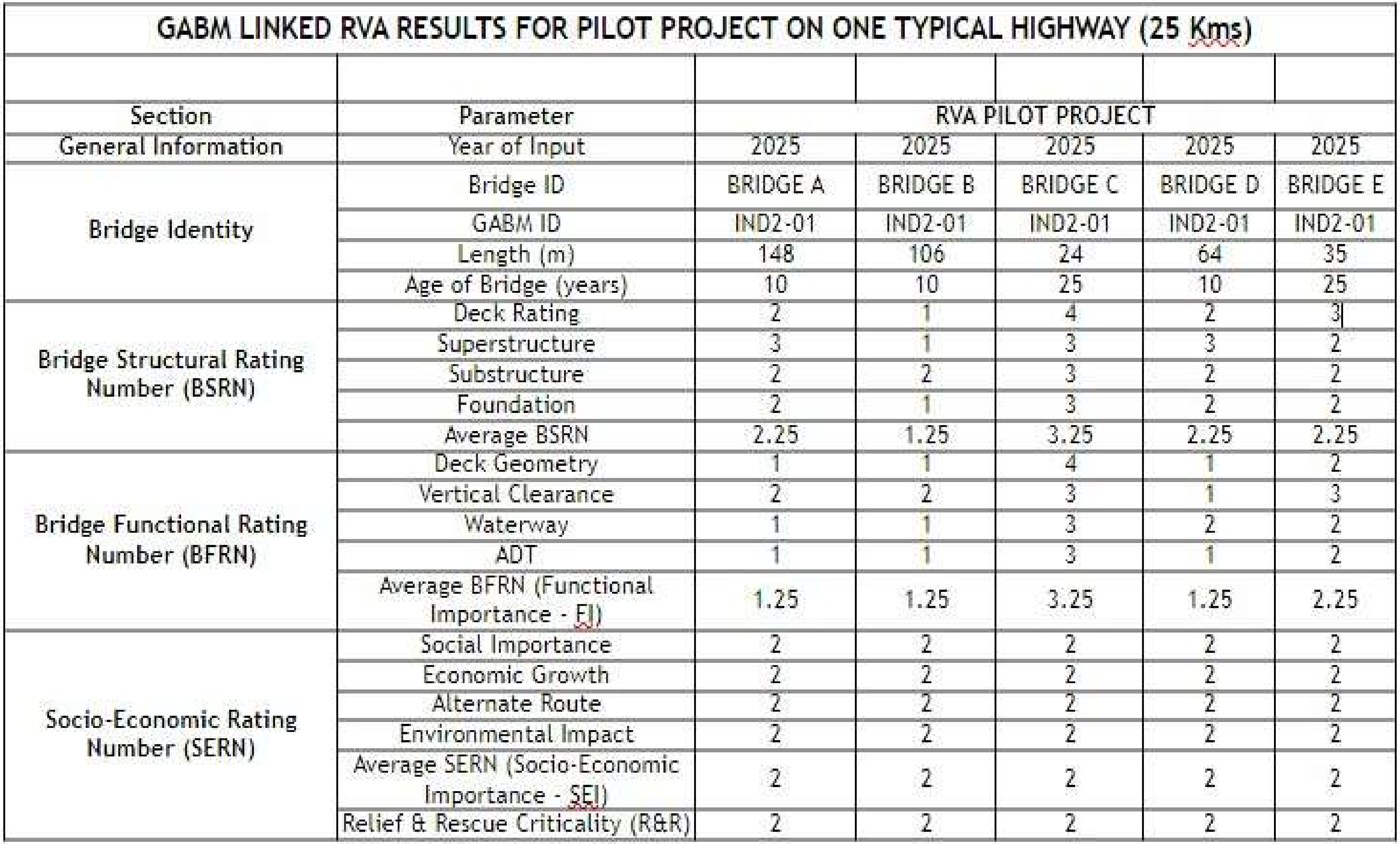
Compute a composite score as a weighted sum of normalised indicator scores:
All five criteria do not equally decide on the criticality of the bridge. Higher hazard exposure would entail higher percentage to Structural Vulnerability and Relief and Rescue criticality. Similarly lower Hazard exposure would mean a stable region where the Socio-Economic and Functional Importance would gain more percentage. Typically the matrix will help us in evolving the Risk Score.

Example: Two Bridge having the following score for each of the criteria

Bridge ONE				Bridge TWO			
CRITERIA	SCORE	PERCENTAGE	RISK SCORE	CRITERIA	SCORE	PERCENTAGE	RISK SCORE
H	1	20.00%	2.6	H	5	100.00%	19
S	1	20.00%		S	5	125.00%	
F	1	100.00%		F	5	15.00%	
SE	1	100.00%		SE	5	15.00%	
RR	1	20.00%		RR	5	125.00%	

Step 5 - Map composite score to intervention categories

Composite Risk Scoring		
CLASSIFICATION	DESCRIPTION	SCORE
Low Risk	Routine monitoring sufficient	2.5 to 6.5
Moderate Risk	Needs preventive maintenance /strengthening	6.6 to 10
High Risk	Prioritised for retrofitting or major strengthening	10.1 to 14
Extreme Risk	Immediate intervention or replacement required	> 14.1



GABM LINKED RVA RESULTS FOR PILOT PROJECT ON ONE TYPICAL HIGHWAY (25 Kms)

Section	Parameter	RVA PILOT PROJECT				
General Information	Year of Input	2025	2025	2025	2025	2025
Bridge Identity	Bridge ID	BRIDGE A	BRIDGE B	BRIDGE C	BRIDGE D	BRIDGE E
	GABM ID	IND2-01	IND2-01	IND2-01	IND2-01	IND2-01
	Length (m)	148	106	24	64	35
	Age of Bridge (years)	10	10	25	10	25
Bridge Structural Rating Number (BSRN)	Deck Rating	2	1	4	2	3
	Superstructure	3	1	3	3	2
	Substructure	2	2	3	2	2
	Foundation	2	1	3	2	2
	Average BSRN	2.25	1.25	3.25	2.25	2.25
Bridge Functional Rating Number (BFRN)	Deck Geometry	1	1	4	1	2
	Vertical Clearance	2	2	3	1	3
	Waterway	1	1	3	2	2
	ADT	1	1	3	1	2
	Average BFRN (Functional Importance - FI)	1.25	1.25	3.25	1.25	2.25
Socio-Economic Rating Number (SERN)	Social Importance	2	2	2	2	2
	Economic Growth	2	2	2	2	2
	Alternate Route	2	2	2	2	2
	Environmental Impact	2	2	2	2	2
	Average SERN (Socio-Economic Importance - SEI)	2	2	2	2	2
	Relief & Rescue Criticality (R&R)	2	2	2	2	2

Cause Matrix (GABM Input)	Impact (M1)	1	1	1	1	2
	Abrasion (M2)	1	1	1	1	2
	Erosion (M3)	1	1	1	1	1
	Overload (M4)	2	1	3	1	2
	Fatigue (M5)	1	1	2	1	2
	Temperature (P1)	2	1	2	1	2
	Shrinkage (P2)	2	1	2	1	2
	Settlement (P3)	1	1	2	1	1
	Chloride Attack (C1)	2	1	2	1	2
	Sulphates (C2)	2	1	2	1	1
	Carbonation (C3)	2	1	2	1	1
	Alkali-Aggregate (C4)	2	1	2	1	1
	Total of Cause Ratings	19	12	22	12	19
	Hazard Zone	WEST	WEST	WEST	WEST	WEST
RISK RATING						
	Flooding	4	4	4	4	4
	Cyclone	3	3	3	3	3
	Landslide	2	2	2	2	2
	Earthquake	2	2	2	2	2
RISK INDEX						
RISK INDEX	FLOODING	0.21	0.2	0.26	0.21	0.24
	CYCLONE	0.18	0.18	0.25	0.18	0.22
	LANDSLIDE	0.22	0.21	0.31	0.22	0.26
	EARTHQUAKE	0.22	0.21	0.31	0.22	0.26
	TRANSFER TO MCDM	0.21	0.2	0.2825	0.2075	0.245

Use threshold bands to decide action necessity. Example mapping [scale 1-5 scores]:

- **Low risk:** Routine monitoring and scheduled minor maintenance. No immediate structural work needed.
- **Moderate risk:** Preventive maintenance, targeted repairs, enhanced monitoring [install SHM sensors]. Plan upgrade within short-term cycle [2-5 years].
- **High risk:** Prioritise for structural strengthening and detailed engineering assessment. Consider temporary load restrictions and emergency planning. Immediate funding allocation recommended.
- **Extreme risk:** Immediate intervention required — emergency shoring, closure and diversion if needed, and fast-track rehabilitation or replacement. These bridges are prioritised for disaster response plans.

Impact analysis with respect to likelyhood, severity, deterioration status

Impact analysis combines three connected pieces of information to judge what a hazard will do to a bridge: how likely the hazardous event is [likelihood], what the consequences are if it occurs [severity], and how the bridge's current physical state [deterioration status] changes both of those. Treating these three elements together produces a realistic, actionable picture of impact.

Likelihood is the probability that a hazard event of a given intensity will affect the bridge within a specified time frame. It is derived from historical records [return periods], recent trends [example shortening of "100-year" events], and forward-looking projections [climate/scenario models, seismic hazard maps]. Likelihood is location- and hazard-specific: example river stage exceeding frequency for floods, peak ground acceleration for earthquakes, or annual maximum wind speeds for cyclones. In practice, likelihood is expressed as a recurrence interval or as a normalised score [example 1-5] for inclusion in matrices. Severity captures the magnitude of consequences when the hazard impacts the bridge. Severity has multiple dimensions: structural [partial/complete collapse, loss of load capacity], functional [hours/days/weeks of route closure], socio-economic [value of disrupted trade, access to hospitals], and safety [injuries or fatalities]. Severity depends on hazard intensity, the bridge's vulnerability, and the presence of cascading effects [loss of power supply, blocked evacuation routes]. Severity is usually estimated using damage models, historical impact records, fragility curves, or expert judgement and is again mapped to a graded scale for decision tools[27].

Deterioration status is an internal modifier: it transforms the same hazard into a different outcome. Two identical hazard events can produce very different impacts depending on foundation scour, reinforcement corrosion, fatigue cracking, bearing damage, or previous repairs. Deterioration status should be quantified, using inspection outcomes, non-destructive testing [NDT] metrics, structural health monitoring [SHM] records, and derived indicators such as residual capacity or remaining Balance Service Life [BSL/ABSL/MSL]. A bridge with significant deterioration raises the effective severity for a given hazard and sometimes the likelihood indirectly [for example, scour that exposes foundations increases the chance of collapse under moderate floods].

RISK INDICATOR MATRIX helps in definition of necessity of rehabilitation intervention for the bridge.

Multi-Criteria Decision-Making in RVA:

The three elements interact non-linearly: deterioration can multiply the effective severity and in some cases make low-likelihood events effectively more dangerous [example rare moderate floods causing collapse due to undermined foundations]. Therefore, credible impact analysis does not treat likelihood and severity independently; it explicitly adjusts severity by current deterioration status and models scenarios across return periods [short-term, mid-term, long-term].

Along with these three factors one has to account for Functional and Socio-economic parameters in conjunction with Financial due diligence. Natural hazards occurrences shows dynamism in terms of its frequency and severity. Entire world is witness to such dynamism. This has caught the engineering fraternity surprised and unprepared. Infrastructure endures the most impact of this dynamism. Designs of infrastructure and bridges in particular, do account for normal forces of natural hazards. Geographical vulnerability dictate the design practices. Dynamism results in negating assumptions of severity and frequency. The incremental forces influence structures, triggering an exponential deterioration process. Global surge in infrastructure construction demanded economical solutions. The concept of “Design and Built” adopted to select the most economical design. Absence of stringent resilience requirements compromise long-term survival possibilities. We all understand that **Resilient bridges show a higher probability of survival.**

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

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

The need for a shift from Mono-Criterion Decision-Making process to a multi-criteria process needed. This need arises from the growing importance of ensuring the resilience of the entire logistics network.

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

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

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

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

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

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

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

Define Priority consideration and linking to RVA

In the context of bridge management and disaster risk reduction, priority consideration refers to the systematic process of determining which bridges require immediate attention, intervention, or resource allocation based on their overall level of risk and importance within the network. Prioritization is not merely a technical ranking exercise—it represents a critical decision-making step that transforms the results of the Risk and Vulnerability Assessment [RVA] into actionable strategies. The aim is to identify which bridges are most likely to fail or cause severe disruption during a hazard event, and which ones hold the highest functional and socio-economic importance. By linking prioritization to RVA, decision-makers can ensure that rehabilitation, retrofitting, and maintenance programs are data-driven, equitable, and cost-effective.

Priority in this context is defined by the combination of three main components—hazard exposure, structural vulnerability, and consequence of failure. A bridge exposed to multiple natural hazards such as floods, earthquakes, or landslides, and showing signs of material deterioration or outdated design standards, will naturally occupy a higher priority level. However, technical factors alone are insufficient. The functional and socio-economic criticality of a bridge—such as its role in connecting hospitals, industrial zones, or evacuation routes—also plays a central role. Hence, the concept of priority is multidimensional, merging engineering, environmental, and social perspectives into a unified evaluation framework.

To link RVA outcomes to prioritisation, the process begins with identifying and quantifying hazards and exposures for each bridge. This includes mapping bridges in floodplains, seismic zones, or areas prone to scour and landslides. The next step involves assessing vulnerability, which considers both physical conditions [age, design life, material degradation, maintenance history] and functional dependence [traffic load, availability of alternate routes, redundancy in the network]. Once vulnerability and exposure data are integrated, the risk indicator matrix can be developed to express the combined influence of hazard likelihood, severity, and deterioration status. This matrix helps in categorising bridges into different risk levels—low, moderate, high, or critical.

The priority definition process can be structured as a step-by-step approach. First, compile all hazard, exposure, and vulnerability data from RVA results. Second, assign standardised scores or weights to each factor—such as hazard intensity, bridge condition, structural type, and functional importance. Third, multiply or combine these weighted indicators to generate an overall risk score for each bridge. Fourth, rank all bridges within the portfolio based on these scores, while considering external factors such as economic value, population served, or emergency connectivity. Finally, validate the results through expert review, stakeholder consultation, and field verification to ensure that the prioritization truly reflects ground realities and institutional goals.

The output of this process is a priority ranking or classification, which helps authorities to plan interventions in a phased manner. Bridges categorised as "high priority" may require immediate structural assessment, retrofitting, or replacement, while "medium priority" bridges might be scheduled for regular monitoring and maintenance. "Low priority" bridges, though safe, should still be tracked to detect early signs of deterioration.

Ultimately, the linkage between RVA and prioritization establishes a logical bridge between scientific assessment and policy implementation. RVA provides the analytical foundation—quantifying risks, vulnerabilities, and adaptive capacities—while prioritization translates this information into management action[28]. It ensures that limited resources are directed first to the bridges whose failure would have the most severe technical, economic, and social consequences. In doing so, the process not only strengthens the resilience of the transport network but also enhances disaster preparedness, public safety, and long-term infrastructure sustainability.

Net Zero pathway

Carbon dioxide [CO_2] percentage in atmosphere plays a significant role in the ongoing global warming. During the immediate past decade 2010 to 2020 the atmospheric concentration of CO_2 was recorded to have witnessed a 2.5 ppm per year increase over the one recorded in 1970-1980. Global warming is causing dynamic changes in natural hazard occurrence frequency and severity. Construction industry contributes over 40% of carbon emission globally. UNDRR adopted the goal to ensure that this emission is under control. Many industry sectors are working towards the NET ZERO carbon. Since construction sector is the prime contributor achieving Net Zero carbon structures is critical for reducing impact of global warming. Cement results in 7 to 8 % of global green house emissions.

The net zero pathway to be successful within construction industry, will entail massive investments, technological and cultural difficulties in identification and evolving alternative material that do not bring embodied carbon footprints. Engineers and researchers will need to define materials with near zero carbon footprint. Such efforts have been a long haul. Feasibility of this effort will hinge on proper legal framework and implementation of policy decisions that promote and prioritize investments and procurement of such materials. Concrete [the main material for bridge construction] production leads to carbon emission. This constitutes the main source of embodied carbon emission in bridges.

Embodied carbon emission constitute over 3 to 4 percentage of net total emission which translates to over 10 percentage of carbon emission within transport sector. Infrastructure construction, operation and maintenance being the main contributor of such embodied emission. Low emission material evolution will help reduce this embodied carbon emission.

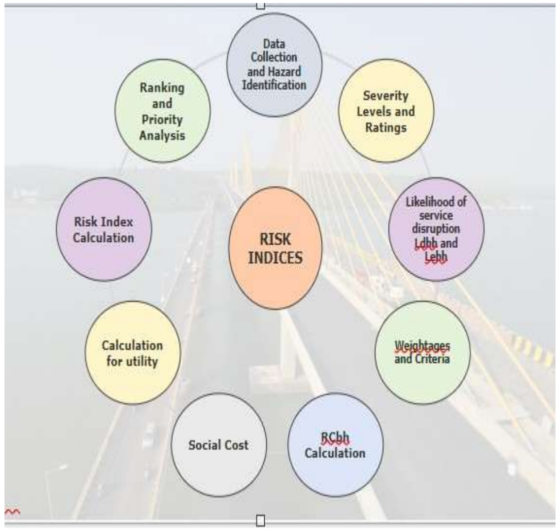
Transport infrastructure has now gained recognition as a major enabler of economic growth and stability. Sustainable infrastructure resulting from enhanced resilience of bridges, will result in increased confidence on the logistic system in general aiding enhanced investments and growth. Owners of bridges will need to accept this reality. Enhanced budgetary provisions are essential to ensure all the ageing bridges are maintained properly in a correct technical manner. This methodologies will need to meet the emerging stringent energy and carbon footprint requirements. Research to make the rehabilitation systems more sustainable and net zero should be the goal. Legal provisions need to be adopted that make it mandatory for implementation of BMS nationally to ensure that all bridges on critical network are attended to and enhanced resilience is achieved.

Bridge demography attains criticality. Globally most of the infrastructure owes its origin to post world war era. That makes the age of majority of the infrastructure to be over 80 years. Ageing bridges need more rehabilitation implying more embodied carbon emission. Most of the present day rehabilitation procedures rely heavily on usage of chemicals in conjunction with cement, steel and other materials which are known contributors of embodied carbon emission. The demography of ageing bridges adds to the problems. Implementation of BMS judiciously ably supported by budgetary provisions can reduce this continued addition to embodied carbon emission. Budgets will need to be evolved from the Bill of Quantities [BOQ] that are generated at the end of bridge inspection program. BOQ generally misses on the costs related to indirect costs incurred during rehabilitation program. Such indirect costs include cost of alternate route creation during the rehabilitation work that needs closure of the all the lanes on the bridge. Partial closure of lanes also adds to indirect costs due to increased wait time, delay in final completion of journey, escalation costs, human errors and inefficiency, loss of productivity, cost overruns, design changes etc. Budgets will need to account for all such missed items of costs during BOQ stage. Such costs could also include socio-economic indirect costs to make the financial decision making easy and transparent.

Ageing infrastructure requires huge rehabilitation efforts. Fiber reinforced concrete [FRC] is one such emerging technology that can provide a substitute to conventional reinforced concrete system. Carbon fiber filaments take the systems nearer to meet the requirements of reduced carbon footprint, maintaining the strength and durability standards. FRC has a huge structural application potential as it is light weight, high strength, low density, high modulus of elasticity. FRC also has immense durability which arises from its resistance to environmental degradation. FRC exhibit adequate compression strength, tensile strength along with flexural and shear properties. Conventional reinforced concrete have steel. This steel is prone to corrosion which reduces the durability of the such concrete. FRC overcomes this problem rendering it as a leading sustainable concrete option.

Today, globally the demand for delivering highly efficient infrastructure which comply with the carbon footprint and sustainable requirements is a challenge. When over 40 billion tons of cement is used, even 30 to 45 percent reduction in embodied carbon will yield high efficiency in sustainability requirements. Introduction of Supplementary Cementious materials like fly-ash or slag also help in reducing the embodied carbon in the concrete. Limestone calcined clay cement, Cold-formed steel, Cross laminate timber, 3D print construction are few emerging technologies which offer an option. Various attempts to use recycle aggregates also have shown promising results in reduction of carbon footprint. Circular economic approach is extending the use of recycled material beyond aggregates to include recycled fiber reinforcement. Using FRC provides an opportunity to enhance concrete performance and durability and also resulting in reduced embodied carbon footprint.

Research is ongoing in many universities and research bodies to ensure cost efficiency and reduction in unwarranted long term behavior in concrete which demand rehabilitation and constant attention.



CONCLUSION:

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 in this study bridges the gap between traditional engineering inspection methods and modern risk-based approaches. It recognises that risk is a multidimensional 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.

Pilot project conducted on a stretch of 25 Kms of highway yielded results for Risk and Vulnerability Index that can be then used in Multi-Criteria Decision-Making tool of GABM to define the priority of bridges that can be provided with funds for rehabilitation and resilience enhancement. This pilot project indicated the positive outcome of the research. Criticality of bridges which have high risk to natural hazard are highlighted by the Risk Vulnerability Analysis.

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 emphasise the need for continuous monitoring, stakeholder engagement, and data integration. Risk is not static; it evolves with environmental change, urban expansion, and infrastructural aging. 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, this study concludes 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 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.

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