



UBMS RESEARCH GROUP [URG]

SHAPING THE FUTURE OF BRIDGE MANAGEMENT

NAVIGATING FROM DETERIORATED TO RESILIENT BRIDGES

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NAVIGATING FROM DETERIORATED TO RESILIENT BRIDGES

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DEDICATED TO

GLOBAL FRATERNITY OF BRIDGE MANAGEMENT ENGINEERS

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BACKGROUND PREAMBLE AND INTRODUCTION TO FOUR HAZARDS

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A) PREAMBLE:

UBMS Research Group [URG] have a lineage starting from 2003, when Sachidanand Joshi started the research to evolve a Bridge Management System for India. In 2020, URG formation ensured sustained research in bridge management systems. During implementation of the evolved Indian Bridge Management System from 2015 to 2018, identified shortcomings in the process to implement bridge management resulted in evolution of IBMS. Deemed essential was to integrate the most innovative technologies that were emerging on the horizon. Technologies like videography-using UAV/ Drones, use of photogrammetry tools to create 3D models, creation of partial or full bridge 3D model using UBMS data, partial usage of Bridge Information models, Structural Health Monitoring were all deemed essential to be incorporated within the domain of Bridge Management.

Formation of UBMS Research Group took place in 2022, to sustain and continue with the research in bridge management. The same year, Morbi Bridge Collapse that resulted in death of over 140 innocent people. The urge to evolve a bridge management system affordable for owners of micro and small inventory drove URG to evolve Global Analytics for Bridge Management [**GABM**]. URG worked on the required modifications and delivered GABM by early 2023. GABM empowers small Municipal Corporation without huge budgets to implement Bridge management.

The events of 2023 related to impact of Natural Hazards on the road network and more specifically the bridges lead to inclusion of Risk Assessment for impact of natural hazards on bridges. A module, which assess the impact of natural hazards on bridges, was included in GABM. The entire software application is available on our website [<https://ubmsresearchgroup.com>] for all to gain mastery.

Evolution required to implement risk assessment opened a Pandora box of unsolved issues. Rescue and relief organizations like NDMA and NIDM in India, need clarity on the best route to reach the hazard zone. Risk assessment alone was insufficient for the Rescue and Relief organizations to utilize GABM. Essentially required was to identify with certain amount of certainty the Impact of the occurrence of natural hazard on the bridges on the route identified be evaluated. Bridges all over the world are aging. Aging bridges have deterioration in varying degree. It is unknown how these deteriorated bridges will perform when exposed to forces of natural hazards. Their performance determines the success of Rescue and Relief operation, aimed to save human lives in the golden hour post occurrence of the natural hazard.

Globally, we all are witness to score of people dying in remote areas due to delay in relief and rescue reaching the most needed population. One of the main reason is collapse of bridges connecting the area. URG intend to use our expertise in bridge management to evolve the tool that could define resilient bridges.

URG is committed to evolve the method to identify existing deteriorated bridges. Then determine how the force of natural hazards affects these deteriorated bridges. The tool evolved will be useful to ascertain which of the route is safe to use when relief and rescue is to be provided. It will define the capability of the existing deteriorated bridge to withstand the natural hazard. The tool will identify the intensity of natural hazard, which the bridge will be able to withstand.

UBMS Research Group [URG] submitted their Voluntary Commitment under the Sendai Framework for Voluntary Commitment [SFVC] in October 2023. United Nations office for Disaster Risk Reduction accepted the same with Global Implications. Two deliverables are part of the commitment given in SFVC. The deliverables are as under:

- a) Provide a tool to enhance the resilience of existing deteriorated bridges in the high-risk zones for natural hazards using Global Analytics for Bridge Management.
- b) A set of papers outlining our methodologies, which enable us to evolve the tool. The set of papers published as a Book titled "Navigating from Deteriorated to Resilient Bridges".

India's commitment to evolve resilient infrastructure influenced URG. URG's Voluntary Sendai Commitment made under Sendai framework for disaster risk reduction, aims to use our expertise in bridge management to identify resilience in bridges. Our commitment under SFVC aims to "Provide a tool to enhance the resilience of existing deteriorated bridges in the high-risk zones for natural hazards using Global Analytics for Bridge Management". The entire work on this commitment is likely to finish before October 2025.

This book titled "**NAVIGATING FROM DETERIORATED TO RESILIENT BRIDGES**"; is part of UBMS Research Group's Voluntary Commitment under the Sendai Commitment of United Nations Disaster Risk Reduction [UNDRR]. UBMS Research Group published this research documentation under ISBN no: **978-93-6013-596-6**.

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First three chapters comprise of Initial background, problem definition, and approach to research. The chapters after that outline the implementation of the key findings of the research to resolve the problem. The entire book is available on our website (<https://ubmsresearchgroup.com/blog-grid/>)

B) INTRODUCTION:

The world over, demography of bridges is aging. Deterioration is part of aging process in bridges. Forces of natural hazards affect bridges. The degree of impact of these forces will vary in different bridges based on the level of original deterioration in the bridge. Aging bridges with deterioration show varying degree of resilience when exposed to forces of natural hazards. The required solution is to evaluate a logical definition to the level of impact that the forces of natural hazard will have on existing aged and deteriorated bridges.

The four natural hazards, based on the statistical data of hazards having impact in India are Earthquakes, Flooding, Cyclones, and Landslides. Of these Earthquake and Cyclone are primary hazards and Flooding and Landslides are secondary

hazards. Initiation of secondary hazards happens after the occurrence of any of the primary hazards. Below we have compiled the definition and the characteristics of the four hazards. Majorly the information collated is from different sources in one place for ease of understanding of the forces of natural hazards we are dealing with.

1. Earthquake

Earthquake is defined by *USA's Geological Survey*² and adopted by UNDRR in their publication *Hazard Information Profile*¹ as "Earthquake is a term used to describe both sudden slip on a fault, and the resulting ground shaking and radiated seismic energy caused by the slip, or by volcanic or magmatic activity, or other sudden stress changes in the Earth".

Based on this description, many types of earthquakes exist. Below we have summarized the key characteristics of various types of earthquakes based on information from *Hazard Information Profile*

Key Characteristics of Earthquake Hazards

Earthquake hazards encompass a range of characteristics that can pose threats to human life, infrastructure, and the environment. These hazards are associated with the seismic energy released during an earthquake event.

A. Ground Shaking:

The primary and immediate hazard is the ground shaking caused by the release of seismic energy. The intensity and duration of shaking at any particular location depend on factors such as the earthquake's magnitude, depth, and proximity to the epicentre.

B. Surface Rupture:

In some earthquakes, the ground may rupture along the fault line, causing displacement of the Earth's surface. This surface rupture can damage structures, roads, and other infrastructure directly above the fault.

C. Ground Rupture:

Ground rupture occurs when the Earth's surface breaks along the fault line, resulting in visible displacement. This can affect the alignment of roads, railways, and other structures.

D. Aftershocks:

Aftershocks are smaller seismic events that follow the main earthquake. They can occur in the minutes, days, or even months after the initial shock, potentially causing additional damage and hampering recovery efforts.

E. Liquefaction:

In areas with loose, water-saturated soils will lose its strength temporarily due to seismic shaking. This phenomenon, known as

liquefaction, can lead to the sinking or tilting of structures built on such soils.

F. Tsunamis:

Underwater earthquakes can generate tsunamis, which are large oceanic waves capable of causing widespread coastal damage. Tsunamis can inundate low-lying coastal areas and islands, posing a significant threat to life and property.

G. Surface Waves:

Surface waves generated by an earthquake can travel through the Earth's crust and cause secondary ground shaking at the surface. These waves can amplify the overall seismic hazard.

H. Fault Rupture Displacement:

The amount of displacement along a fault during an earthquake can influence the degree of ground shaking and damage. Significant seismic hazards often result in greater displacement.

I. Seismic Landslides:

Earthquakes can trigger landslides on slopes and hillsides, leading to the movement of rocks, soil, and debris. Landslides can bury infrastructure, disrupt transportation routes, and pose additional risks.

J. Fire:

Earthquakes can rupture gas lines and damage electrical systems, leading to the potential for fires. Post-earthquake fires can be a secondary hazard, causing additional destruction.

K. Structural and Non-Structural Damage:

Buildings, bridges, and other structures can suffer damage or collapse during an earthquake. Non-structural elements like windows, facades, and ceilings may also pose hazards.

These characteristics are crucial for earthquake preparedness, risk assessment, and the development of effective mitigation strategies to minimize the impact of seismic events on communities and infrastructure. Building codes and construction practices in seismically active regions often incorporate measures to reduce vulnerability to these hazards.

2. Flooding

Flooding is a secondary hazard. Flooding pose diverse and complex threats to communities and the environment, stemming from variety of factors. The manifestation of these hazards, characterized by intense and rapid flooding, can have profound impacts on vulnerable areas. Understanding the key features, including urban flooding, coastal erosion, and infrastructure failures, is pivotal for effective flood risk management. Community awareness, preparedness, and resilient infrastructure play crucial roles in mitigating the impact of flooding,

emphasizing the need for proactive measures and collaboration among local authorities and emergency responders.

Key Characteristics of Flooding Hazards

Flooding hazards can manifest in various forms, and a range of features and factors that contribute to their potential impact on communities and the environment characterizes them. The key characteristics are:

A. Heavy Rainfall:

Intense and prolonged periods of rainfall can lead to increased runoff, causing rivers, streams, and other water bodies to overflow their normal boundaries or banks.

B. Storm Surge:

Storm surges occur in coastal areas during tropical storms or hurricanes, where strong winds and low atmospheric pressure cause a temporary rise in sea level, leading to coastal flooding.

C. Snowmelt:

Rapid melting of snow, especially in mountainous regions, can contribute to increased water flow in rivers and streams, leading to flooding downstream.

D. Ice Jams:

In cold climates, ice jams can occur when floating ice accumulates and obstructs the flow of rivers, causing water to back up and flood adjacent areas.

E. Flash Flooding:

Rapid onset and intense flooding, often caused by heavy rainfall, dam breaks, or sudden release of water, characterize flash floods.

F. Riverine Flooding:

Overflow of rivers and streams due to prolonged rainfall or snowmelt can lead to riverine flooding. This type of flooding is more gradual compared to flash flooding.

G. Urban Flooding:

Urban areas with impervious surfaces, such as pavements and buildings, can experience flooding due to reduced infiltration and increased runoff during heavy rainfall.

H. Coastal Erosion:

Flooding hazards in coastal areas are often associated with erosion caused by storm surges, high waves, and changing sea levels.

I. Topography:

Low-lying areas, river valleys, and coastal plains are more susceptible to flooding due to their natural vulnerability to water accumulation.

J. Land Use Changes:

Human activities such as deforestation, urbanization, and alterations to natural drainage patterns can influence the occurrence and severity of flooding.

K. Climate Change:

Changes in climate patterns, including increased frequency and intensity of extreme weather events, can contribute to heightened flooding risks.

L. Infrastructure Failures:

Dam or levee failures, as well as inadequate drainage systems, can exacerbate flooding hazards, leading to more extensive and severe flooding.

M. Hydrological Conditions:

Saturation of soils, high groundwater levels, and the capacity of water bodies to handle increased water flow are critical factors influencing flooding.

These characteristics is essential for effective flood risk management, including prevention, early warning systems, and the development of resilient infrastructure in vulnerable areas. Local authorities, emergency responders, and communities play crucial roles in adapting to and mitigating the impacts of flooding.

3. Cyclones

Cyclones, also known as hurricanes or typhoons, are formidable weather phenomena marked by powerful winds, heavy rainfall, and storm surges. With rotating winds categorized on scales like the Saffir-Simpson Hurricane Wind Scale, cyclones exhibit low atmospheric pressure at their center, known as the eye, surrounded by the eyewall. This intense weather system brings forth challenges such as torrential rainfall, storm surges, and even tornadoes, with their size, intensity, and movement patterns varying widely. A dependence on warm ocean waters and distinct seasonal patterns makes understanding these characteristics essential for effective preparedness and response strategies to safeguard communities and infrastructure.

Key Characteristics of Cyclones Hazards

Cyclones in different regions are powerful and destructive weather phenomena characterized by strong winds, heavy rainfall, and storm surges. The key characteristics are:

A. Strong Winds:

Cyclones known for their intense, rotating winds that can reach extremely high speeds. Categorized as the Hurricane Wind Scale or the equivalent regional scale.

B. Low Atmospheric Pressure:

Cyclones are associated with low-pressure systems at their center, known as the eye. The low atmospheric pressure contributes to the inward flow of surrounding air, creating the characteristic wind rotation.

C. Eye and Eyewall:

The center of a cyclone called the eye is a relatively calm and clear area. Surrounding the eye is the eyewall, where the strongest winds and heaviest rainfall occur.

D. Heavy Rainfall:

Cyclones bring intense rainfall, often leading to flooding. The heavy precipitation can result in river overflow, flash floods, and landslides, posing significant risks to communities in the cyclone's path.

E. Storm Surges:

Cyclones generate storm surges, which are abnormal rises in sea levels caused by the combination of strong winds and low atmospheric pressure. Such surges can lead to coastal flooding and pose a serious threat to coastal communities.

F. Tornadoes:

Cyclones can spawn tornadoes, particularly in the outer bands of the storm. Such tornadoes can cause additional localized damage and pose a threat to life and property.

G. Size and Intensity Variability:

Cyclones vary widely in size and intensity. Some may be compact with very strong winds, while others may be larger with less intense winds. The size and intensity of a cyclone influences the extent of its impact on affected areas.

H. Movement and Track:

Cyclones move across the ocean in a generally westward direction due to the prevailing easterly trade winds. The track and speed of a cyclone can influence the areas it affects and the duration of its impact.

I. Warm Ocean Water Dependency:

Cyclones form and intensify over warm ocean waters (usually above 26.5 degrees Celsius or 80 degrees Fahrenheit). The warm water provides the energy needed for the cyclone's development and strengthening.

J. Seasonal Patterns:

Cyclones have specific seasons during which they are more likely to occur. In the Atlantic and eastern Pacific, hurricane season typically spans from June to November. In the western North Pacific, typhoon season is year-round, with a peak from June to November. North Indian Cyclone season extends from April to December. The peak lies between May to November. South West Indian cyclone season starts from November and extends to April

These characteristics are crucial for developing effective preparedness and response strategies to mitigate the impact of cyclones on communities and infrastructure.

4. Landslide

Landslide are secondary hazards. Landslides encompass a diverse range of manifestations influenced by geological, topographical, climatic, and human factors. This various characteristics are associated with landslide hazards, including slope instability, precipitation and water saturation, geological conditions, topography, vegetation cover, previous landslides, earthquakes and seismic activity, human activities, land use planning, and climate change. Understanding these factors is essential for effective assessment and mitigation of landslide risks, involving interdisciplinary approaches and monitoring systems to safeguard human settlements and infrastructure from potential landslides.

Key Characteristics of Landslide Hazards

Landslide hazards can manifest in various ways, and their characteristics depend on factors such as geological, topographical, climatic, and human-induced influences. The key characteristics are

A. Slope Instability:

Landslide hazards linked to slopes, which are susceptible to instability. Slope failures can occur on hillsides, mountains, or cliffs due to a variety of factors.

B. Precipitation and Water Saturation:

Heavy or prolonged rainfall can saturate the soil, making it more prone to landslides. Water acts as a lubricant, reducing the friction between soil particles and increasing the likelihood of slope failure.

C. Geological Conditions:

The type of geological material present in an area influences landslide susceptibility. Weak or poorly consolidated rocks, clay-rich soils, and loose unconsolidated deposits are more prone to landslides.

D. Topography:

Steep slopes are more susceptible to landslides, as the gravitational force acting on the slope is greater. Additionally, the

shape and configuration of the land, such as concave slopes, can contribute to landslide hazards.

E. Vegetation Cover:

The presence or absence of vegetation can influence slope stability. Root systems help bind soil particles together, reducing the risk of erosion and landslides. Deforestation or removal of vegetation can increase landslide susceptibility.

F. Previous Landslides:

Areas that have experienced landslides in the past are more likely to be prone to future landslides. Historical records of landslides in an area can be indicative of ongoing susceptibility.

G. Earthquakes and Seismic Activity:

Seismic events can trigger landslides, especially in areas with steep slopes. Ground shaking can destabilize the soil, leading to slope failures.

H. Human Activities:

Human activities, such as excavation, construction, mining, or changes in land use, can alter the natural stability of slopes and contribute to landslide hazards.

I. Land Use Planning:

Poor land use planning, zoning, and inadequate construction practices can increase the vulnerability of areas to landslides. Improperly designed or constructed infrastructure on or near slopes may exacerbate landslide risks.

J. Climate Change:

Changes in climate patterns, including increased rainfall intensity or alterations in precipitation patterns, can influence landslide hazards. Climate change may lead to more frequent or intense rainfall events, increasing landslide susceptibility.

These characteristics are crucial for assessing and mitigating landslide hazards. Landslide risk assessments typically involve a combination of geological, geotechnical, and hydrological investigations, along with monitoring and early warning systems to reduce the impact of potential landslides on human settlements and infrastructure.

C) References

1. Hazard Information Profile: United Nations office for Disaster Risk Reduction International Science Council (ISC) publication, October 2021
2. USA's Geological Survey: <https://www.usgs.gov/>

RESILIENCE IN BRIDGES: BRIDGE MANAGEMENT PERSPECTIVE

**By Atharvi Thorat, Mayuri Tundalwar.
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A) ABSTRACT:

Resilience came to be adapted into the English language in the 17th Century. It originates from the Latin verb "resilience", meaning to rebound or recoil. When one refers to Resilience, it implies the ability to maintain the original status under all normal and adverse situations.

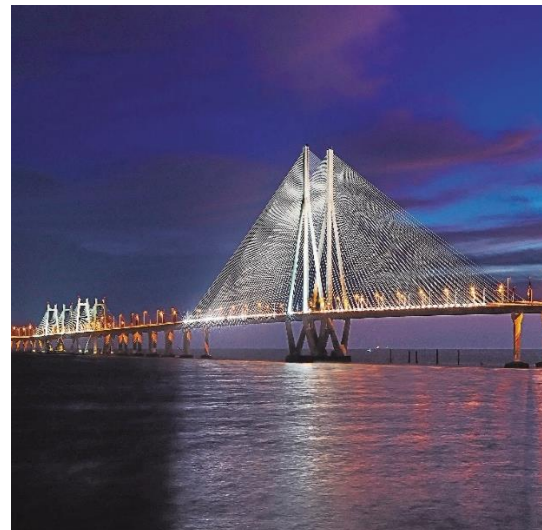
Design, maintenance, and management of critical infrastructure represents a fundamental shift that determines the level of "Resilience" in any asset. Bridges are an integral part of such infrastructure assets. This perspective acknowledges that bridges must provide essential connectivity and be capable of withstanding unexpected challenges and swiftly recovering from disruptions.

Bridge management moves ahead past design and construction. It applies to the entire life cycle management of all the bridges on the transportation network. The principle focus of Bridge management is to define the deterioration process in the bridges. Urgent and most needed bridges get assign priority in fund allocation. Bridge management is a protocol that defines fund optimization.

Resilience in bridges from the perspective of bridge management defines resilience for existing deteriorated bridges.

B) Defining Resilience in Bridges ^[1]

Resilience when applied to bridges is a concept, encompassing the ability of these bridges to endure normal conditions and recover from adverse events. It essentially involves withstanding expected loads and conditions. It also means adapting and recovering when subjected to unforeseen challenges, such as natural disasters, extreme weather, or changes in transportation patterns. Resilience includes adaptability to changing environmental conditions and the ability to recover swiftly in the event of disruptions. Resilience applied to bridges assumes a multi-dimensional nature.



i. The Multi-Dimensional Nature of Resilience

The multi-dimensional nature of resilience in the context of bridge engineering encompasses several interrelated factors that collectively contribute to a bridge's ability to withstand various stressors, adapt to changing conditions, and recover

from disruptive events. These dimensions include structural integrity (in the context of existing deterioration), adaptability, and recovery capacity, each of which plays a distinct but interconnected role in enhancing a bridge's resilience.

- **Structural Integrity:** Structural integrity refers to the bridge's inherent ability to maintain its structural soundness and perform its intended function under various loads and environmental conditions. For existing deteriorated bridges, this dimension refers to the ability to adapt to the situation, which arises from the deterioration within the bridge elements and components.
- **Adaptability:** Adaptability involves the capacity of a bridge to adjust and respond to changing conditions. Original Bridge designs and all rehabilitation interventions provided should essentially incorporate adaptability features to ensure that the structure can continue to function effectively in the future despite evolving circumstances.
- **Recovery Capacity:** The recovery capacity of the bridge relies on the user / owner's preparedness to minimize downtime and recover swiftly after a disruptive event. This should account for deterioration already existing in the bridge structure. The recovery capacity interlinked with the engineering aspects and the philosophy of the user to respond in situations when the adverse events influence the bridge ^[2].

ii. Explore Metrics and Criteria for Quantitative Measurement

Understanding and quantifying the degree of bridge resilience is essential for assessment and planning for improvements. Various metrics and criteria define the quantitative level and measures used in bridge resilience. These metrics may include:

- **Redundancy:** Redundancy refers to the existence of alternative load paths within the bridge structure. A more redundant bridge is less likely to fail if one element is in distress and damaged. If Redundancy not incorporated originally, incorporation of proper measures will bring in the required redundancy.
- **Fragility Analysis:** Fragility analysis involves assessing the bridge's vulnerability to specific stressors. It provides quantitative data on the likelihood of damage or failure under various conditions. Special care needs to ensure that the analysis accounts for the level of deterioration in the bridge.
- **Downtime and Recovery Time:** Measuring the time it takes to repair a bridge and restore its functionality after a disruptive event is a crucial quantitative criterion for assessing recovery capacity.
- **Load-Carrying Capacity:** Quantifying a bridge's load-carrying capacity helps understand its structural integrity. This metric considers factors like the maximum load the bridge can bear under present conditions and the effects of different types of loads.
- **Adaptation Capacity:** Assessing the bridge's ability to adapt to changing environmental conditions can involve various metrics such as projections and the cost-effectiveness of adaptability measures.

Resilience in bridges involves acknowledging the multi-dimensional nature of this concept. Quantitative measurement and assessment of bridge resilience rely on various metrics and criteria. These considerations are essential in the design, maintenance, and management of resilient bridges.

C) Importance of Resilient Bridges^[3]

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

i. Economic Significance of Resilient Bridges

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

ii. Lifelines for Communities

- **Emergency Response:** Resilient bridges play a pivotal role in facilitating emergency response during natural disasters. They are lifelines for first responders, allowing them to reach affected areas swiftly.
- **Daily Commuting:** In everyday life, resilient bridges are the backbone of daily commuting for countless individuals. Resilient bridges ensure that people can go about their daily routines with minimal disruptions.

iii. Long-term durability and Performance

- **Sustainability:** Resilient bridges can endure and recover from adversities reduces the need for frequent repairs and replacements. Such bridges contribute to the long-term sustainability of the region.
- **Minimized Maintenance Costs:** Resilient bridges designed to withstand environmental stressors. When bridges are less prone to damage, there is less need for frequent and expensive maintenance work.

iv. Mitigation of Bridge Failure Risks

- **Safety:** Resilient bridges mitigate the risk of sudden bridge failures, which can have catastrophic consequences. Such bridges provide a level of safety that is vital for both commuters and nearby communities.
- **Economic and Social Continuity:** Resilient Bridges reduce the risk of bridge failures disrupting the flow of goods, services, and people.

This continuity is crucial for economic and social stability before, during and after a natural calamity.

The importance of resilient bridges extends far beyond their physical structure. Resilient bridges are not just a subject of engineering; they are a reason for regional development, community well-being, and economic stability.

D) Historical bridge failures and lessons learned.

Learning from failures provides the much-required inputs to enhance the resilience of bridges. This helps to define the detailed analysis of the root causes behind these failures, seeking to uncover the underlying factors that contributed to their collapse. It encompasses the evolution of engineering codes and standards in response to historical disasters. How these lessons have informed the incorporation of resilience-focused strategies into contemporary bridge design to mitigate the impact of future disasters [4,5,6,7,8,9].

i. Learning from Significant Bridge Failures from the Past:



- One notable example is the Tacoma Narrows Bridge collapse in 1940. Research by Cohn and Cohn (2003), Seroky, and Rabinovitch (2014) extensively analysed the factors leading to this catastrophic failure, emphasising the importance of wind-induced aerodynamic forces.
- Similarly, the Hyatt Regency walkway collapse in Kansas City in 1981 serves as another pivotal case. Fey (1982) conducted a comprehensive investigation into this disaster, revealing that a design modification led to a critical weakening of the structure.
- In the realm of historical bridge failures, events like the Quebec Bridge collapse in 1907 teach lessons. Research by Holgate (1985) extensively examined the factors contributing to this failure, notably inadequate design, quality control issues, and a lack of attention to engineering standards.
- Moreover, a significant body of work by Fell et al. (2015) and Klanker et al. (2019) has analysed historical bridge failures globally, revealing common patterns of design errors during the initial design stage and during rehabilitation works, material deficiencies, and external factors

like natural disasters or accidents that have triggered catastrophic consequences.

- These case studies emphasize the importance of considering a multitude of factors, from design and construction to environmental conditions, and the necessity of rigorous quality control and adherence to engineering standards.

ii. Analysis of the root causes and consequences of historical bridge failures ^[10]:

It is a critical endeavour to understand the vulnerabilities of bridge structures and prevent similar catastrophes in the future:

- One of the fundamental aspects of such analyses is the identification of root causes (or failure mechanisms) behind the bridge failures.
- In-depth investigations often reveal specific weaknesses or vulnerabilities in bridge components, such as structural elements, support systems, or foundations, which contributed to the failure.
- By pinpointing these root causes, engineers and researchers can implement corrective measures, revise design standards, or update maintenance practices to address these weaknesses and enhance the overall resilience of bridge structures.



The learning from the “consequence” of historical bridge failures can be far-reaching, involving not only the structural collapse itself but also extensive societal, economic, and environmental impacts. The immediate consequences may include loss of life, injuries, property damage, and transportation disruptions.

Understanding the analysis of the consequences of historical bridge failures underscores the importance of investing in resilient bridge engineering practices and disaster preparedness to mitigate the potential adverse impacts of such failures in the future. To avoid these causes and consequences early proactive action followed by efforts is necessary.

- Basic design efforts to enhance bridge resilience represent a critical phase in the evolution of bridge engineering, driven by the need to overcome structural vulnerabilities and improve the strength, stability, and overall durability of bridge structures. One significant aspect of these early efforts was the development of fundamental design principles aimed at improving bridge strength and stability.

- Materials were another critical factor in early bridge resilience efforts. The choice of materials evolved from primitive materials like wood and stone to substances that are more durable.
- Innovations in construction techniques were equally integral to the early efforts to enhance bridge resilience. Furthermore, early bridge builders and engineers continually refined their techniques for masonry and stone cutting, enabling the creation of more intricate arches and spans. To address these efforts to enhance bridge resilience encompassed the development of basic design principles, the utilization of superior materials, and innovations in construction techniques during the formative stages of bridge building. These pioneering initiatives set the stage for the evolution of bridge engineering and contributed to the construction of bridges that were not only stronger and more stable but also capable of enduring various challenges over time.
- One of the primary ways, past disasters have shaped modern bridge design is through the evolution of engineering codes and standards.
- Another critical aspect of modern bridge design influenced by past disasters is the integration of resilience-focused strategies.
- In addition to considering the physical aspects of bridge design, resilience-focused strategies also encompass emergency response planning and risk assessments.
- Hence, the impact of past bridge disasters on modern bridge design is multifaceted. It has led to the development of stringent engineering codes and standards, the integration of resilience-focused strategies, the use of advanced materials and construction techniques, and an increased focus on emergency response planning.

E) Identifying various Challenges to Achieve Resilience in Existing Bridges:

Identifying various challenges to achieve resilience in existing bridges is a critical aspect of bridge management and engineering. Achieving resilience in existing bridges is essential to prolong their lifespan and ensure the safety of users.

Enumerating few of the challenges involved ^[11,12]:

- i. Aging Infrastructure:** Over 40% of bridges around the world are aging. Design of aging Bridges may not meet modern resilience standards. Retrofitting and upgrading these older bridges can be complex and expensive.
- ii. Financial Constraints:** Bridge maintenance, repair, and retrofitting require substantial financial resources.
- iii. Changing Environmental Conditions:** The impacts of climate change, including increased temperatures, altered precipitation patterns, and rising sea levels, pose significant challenges to bridge resilience.



Natural Hazards: Bridges in regions prone to natural hazards, such as earthquakes, floods, cyclones, and landslides, face additional challenges. Designing bridges to withstand these hazards and ensuring they can recover quickly is a complex task.

Structural Vulnerabilities: Bridges may have structural vulnerabilities. Identifying and addressing these vulnerabilities is crucial for resilience.

- i. **Complex Regulatory Frameworks:** Complying with evolving safety and environmental regulations can be challenging.
- i. **Technological Advancements:** As technology evolves, there is a need to adapt existing bridges to modern standards.
- i. **Urbanization and Increased Traffic:** Growing urban areas and increased traffic loads put added stress on existing bridges.



Limited Expertise: Identifying the right strategies and technologies for enhancing resilience requires a certain level of expertise.

- i. **Socio-Economic Impacts:** Bridges play a crucial role in local economies. Balancing the need for resilience with minimal disruptions is a challenge.

- i. **Community and Stakeholder Engagement:** Bridge projects often involve multiple stakeholders, including the local community, government agencies, and private entities. Building consensus and addressing concerns can be time-consuming and challenging.

I). Risk Assessment and Management: Identifying potential risks and vulnerabilities in existing bridges and effectively managing them is a complex process that requires thorough analysis.

To address these challenges and achieve resilience in existing bridges, a multi-disciplinary approach is required.

F) **Impact of climate change and natural hazards on bridge resilience**^[2,13]

The impact of climate change and natural hazards on bridge resilience is a topic of critical concern. Climate change, especially rising sea levels and increased flooding presents significant challenges to the resilience of bridges in coastal areas. Several factors increase the vulnerability of bridges:

- **Erosion:** Rising sea levels contribute to coastal erosion, weakening bridge foundations.
- **Increased Flooding:** Elevated sea levels heighten the risk of flooding during storm events, particularly in low-lying coastal regions.
- **Corrosion:** Exposure to saltwater accelerates the corrosion of steel and other bridge materials.
- **Infrastructure Disruption:** Frequent and severe flooding disrupts transportation networks, isolating communities, and hindering emergency response efforts.
- **Resilience Measures:** To enhance bridge resilience against natural hazards, engineers implement various strategies.



In addition to climate change, earthquakes and seismic events represent another significant natural hazard that can profoundly affect bridge resilience. These events subject bridges to dynamic forces that can lead to structural damage and catastrophic failure if not adequately addressed. Key considerations include ^[14]:

- **Vibrations and Lateral Movement:** Earthquakes generate ground motion, causing bridges to vibrate and experience lateral movement.
- **Seismic Retrofitting:** To enhance bridge resilience in seismic-prone regions, engineers frequently implement seismic retrofitting measures.
- **Bridge Type and Design:** The impact of seismic events varies depending on the type and design of the bridge.
- **Local Seismic Hazard:** The local seismic hazard level also influences the retrofitting and design requirements for bridges. Regions with a higher likelihood of significant seismic events necessitate more robust retrofitting measures.
- **Bridge Inspection and Monitoring:** Regular inspections and monitoring systems are crucial for assessing the health of bridges in seismic areas.

In short, climate change-induced rising sea levels and increased flooding, as well as seismic events, are two critical factors that significantly impact the resilience of bridges. Bridge engineers and designers must consider these factors in their

planning and design to ensure the safety and functionality of critical transportation infrastructure.

G) **Structural Considerations to Define Resilience^[15]:**

Structural considerations play a pivotal role in ensuring that a bridge can withstand various stressors, adapt to changing conditions, and recover after disruptive events. It emphasizes the significance of three critical aspects: redundancy, load distribution, and innovative design strategies:

Importance of Redundancy and Load Distribution:

- **Redundancy:** Redundancy ensures that if one component fails or is compromised, the bridge can still safely carry loads. The structure is designed to provide redundancy.
- **Load Distribution:** Load Distribution is the process of efficiently spreading and transferring loads across a bridge's structural elements. A well-designed bridge evenly distributes these loads to prevent localized stress concentrations that could lead to damage or failure.

Innovative Design Strategies for Resilience:

Innovative design strategies go beyond traditional engineering methods to ensure a bridge's ability to withstand a broad spectrum of stressors:

- **Advanced Materials:** Incorporating high-strength, durable, and corrosion-resistant materials into bridge construction can enhance structural resilience.
- **Smart Monitoring Systems:** Integrating sensors and monitoring systems into the bridge's structure allows for real-time data collection.
- **Modular and Prefabricated Components:** Modular construction techniques and prefabricated components allow for faster and more efficient bridge construction.
- **Adaptive and Flexible Design:** Designing bridges with adaptability in mind, such as flexible joints and expansion capabilities, ensures that the structure can withstand dynamic forces.
- **Earthquake-Resistant Design:** In seismic regions, implementing earthquake-resistant design is critical for ensuring structural resilience.
- **Sustainable Design:** Sustainable design practices, contribute to a bridge's overall resilience by reducing the impact of climate change and promoting long-term durability.
- **Geotechnical Considerations:** Understanding the soil and foundation conditions at a bridge's location is essential.

Enhancement in Resilience:

Enhancing structural resilience through redundancy, load distribution, and innovative design has several benefits:

- **Safety:** Redundancy minimizes the risk of catastrophic failure, preventing bridge collapse.
- **Durability:** Load distribution and innovative design principles reduce stress on individual components.
- **Adaptability:** A bridge designed innovatively incorporating redundancy and effective load distribution can adapt to changing conditions and loads.

In conclusion, structural considerations in bridge design, including redundancy, load distribution, and innovative design strategies, are vital for enhancing a bridge's ability to withstand various stressors.

Construction Technologies and Materials in Resilient Bridges

Construction technologies and materials play a critical role in contemporary bridge engineering that underscores the innovative strides made in enhancing the durability, strength, and adaptability of bridge structures. Technological advancements, underpinned by robust materials, are not only incrementing the lifespan of bridges but also increasing their ability to withstand diverse stressors, resulting in resilient bridges.

Advanced Innovative Materials in Resilient Bridge Construction:

Advanced and innovative materials play an important role in constructing resilience. A few examples illustrate this importance.

- High-strength steel and fiber-reinforced composites stand out as key contributors to this endeavor. They offer bridges the structural integrity required to handle heavier loads while maintaining their stability.
- Fiber-reinforced composites are another innovative material that plays a crucial role in resilient bridge construction. They are ideal for constructing bridges that need to support substantial loads while reducing the overall weight of the structure.

Smart Technologies, Sensor Systems for Monitoring and Enhancing Bridge Resilience:

The integration of smart technologies and sensor systems is a transformative development in bridge engineering, as it significantly contributes to the monitoring and enhancement of bridge resilience.

- Sensor systems strategically positioned throughout the bridge structure continuously collect critical data regarding its health and performance.
- These sensors provide real-time information on factors such as structural stress, vibrations, temperature, and environmental conditions.
- Smart technologies, in combination with sensor systems, facilitate predictive maintenance and condition-based assessments.
- This proactive approach to maintenance can significantly extend the lifespan of a bridge, reduce maintenance costs, and minimize the risk of unexpected failures.

- Smart technologies also enable remote monitoring, allowing engineers to access real-time data from bridge sensors via the Internet.
- The data transmitted from sensors aids in decision-making (determining maintenance needs), assessing the safety of the bridge, and providing early warnings in the event of critical conditions.

Therefore, advanced materials and smart technologies are essential elements in the construction of resilient bridges. The combined use of these innovations ensures that bridges are not only durable but also capable of withstanding various challenges, ensuring the safety and longevity of these critical infrastructure components.

H) Conclusion

In conclusion, it provides a comprehensive overview of resilience in bridges from a bridge management perspective. It emphasizes the importance of resilience in bridge design, maintenance, and management, highlighting the multi-dimensional nature of this concept. It discusses the need for quantitative measurement and assessment of bridge resilience, considering metrics such as redundancy, fragility analysis, downtime, load-carrying capacity, and adaptation capacity.



The importance of resilient bridges underscored, as they are not just physical structures but vital conduits of economic development, community well-being, and regional stability. Lessons from historical bridge failures analyzed, emphasizing the importance of understanding root causes and consequences to enhance the resilience of bridges.

Challenges in achieving resilience in existing bridges outlined, ranging from aging infrastructure to changing environmental conditions and financial constraints. The impact of climate change and natural hazards on bridge resilience discussed, highlighting the vulnerability of coastal bridges to erosion and flooding, as well as the seismic risks faced by bridges in earthquake-prone areas.

The structural considerations for defining resilience in bridges, including redundancy, load distribution, and innovative design strategies, emphasized as critical factors in enhancing a bridge's ability to withstand stressors. The use of advanced materials and smart technologies highlighted as pivotal in constructing resilient bridges, extending their lifespan, and improving their ability to withstand various challenges.

Overall, it provides valuable insights into the complex and multifaceted nature of resilience in bridges and underlines the importance of a holistic approach to bridge management and engineering, considering both current challenges and future uncertainties. Resilience in bridges is not only a matter of structural design but also a critical element in promoting economic development, ensuring community well-being, and enhancing the overall stability of regions.

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CHALLENGES OF ESTABLISHING RESILIENCE IN BRIDGES CONSIDERING NATURAL HAZARDS RISK.

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A) Abstract:

The concept of Resilience in infrastructure propagated in the early twentieth century. Over the past few years, the significance of resilience has gained importance. The impact of rapid climate change resulted in resilience gaining importance. Occurrences of Natural hazards have become very unpredictable in terms of periodicity and severity. The impact on infrastructure is humungous. Bridges, which form an important part of infrastructure, bear the brunt. The world over the bridge demography is aging. Deterioration is an integral part of aging bridges.

The challenge of establishing Resilience in aging bridges is very complex and compound. Very little study and documentation can be found in the sphere of transgressing a "**Deteriorated bridge**" to a perfectly resilient bridge. This forms the theme of the entire research. This paper's focus is to define the various façade of the challenges that come to the forefront when we consider natural hazards. Focus is limited to four natural hazards namely Cyclone, Flooding, Landslides, and Earthquakes. The chapter defines the concept of resilience in bridges when we consider these four natural hazards, during the initial design stage. We intend to utilize this design philosophy to extend to deteriorated bridges.

B) Introduction:

Establishing resilience in bridges considering the risk posed by natural hazards is of paramount importance in the field of bridge engineering and management. In the preceding chapter, we highlighted Bridge Resilience from the Bridge Management perspective.

Natural hazards, such as earthquakes, floods, cyclones, landslides, and extreme weather events, have the potential to inflict substantial damage on bridges and disrupt transportation networks. Bridge management to date has dealt with known agents of distress. The occurrences, the severity, and the location were all predictable and defined by the laws of science. This resulted in Bridge management techniques rely on and anchored solidly to sound scientific procedures. When dealing with natural hazards and the impact of climate change, the main factor, which creates the challenges, is the factor of dealing with the **UNKNOWN**. Bridge management will need to venture into the domain of the unknown. The unpredictability of natural hazards occurrence coupled with the fact of near impossibility of the bridge to avoid the impact of the natural hazards, highlights the journey into the unknown.

Bridges the world over are aging. Statistical data suggest the majority of bridges in use the world over are above 50 years of age. The Construction and design philosophy was of the period, which did not account for the safety and rigorous regimes of today, which also account for the probable impact of natural hazards.

The known scenario that emerges is that most bridges are experiencing deterioration with the resultant reduction in capacity, specific reduction in ductility, and decreased plasticity. Deterioration in bridges is a known fact. Aging bridges show deterioration in varying degree. The impact of the existing deterioration on the vulnerability of the bridge to natural hazard and the force of nature is also unknown. This phenomenon is a challenge to research aimed to establish resilience condition from deteriorated state of the bridge.



Herein now, we emphasize the significance of addressing natural hazards in bridge resilience and explore the challenges associated with doing so. It is crucial to understand the impact of climate change on bridge infrastructure, adapt bridges to extreme weather events, and examine case studies of climate-resilient bridge design. This comprehensive approach will provide a deeper understanding of the significance of resilience when considering natural hazards ^[1] .

C) CLIMATE RESILIENCE

Climate resilience in the context of bridge engineering refers to the capacity of bridges and related infrastructure to withstand and recover from the impacts of climate change and extreme weather events. It involves strategies and measures that need to be adapted within bridges to counter the impact of changing climate conditions. The various facades include rising temperatures, increased precipitation, more frequent and severe storms, rising sea levels, and many other challenges. Climate-resilient bridges maintain functionality, structural integrity, and safety under changing environmental circumstances, ensuring continuity within the transportation networks. This results in a reduction of the risk of disruptions caused by climate-related challenges.

i. Impact of climate change on bridge infrastructure

Climate change manifests through various hazards, including increased temperatures, altering precipitation patterns, more frequent and severe storms, and rising sea levels. Each of these hazards has distinct repercussions for bridge infrastructure, ranging from immediate structural damage to long-term deterioration. Understanding the specific impacts is crucial for devising the path to resilient designs and maintenance strategies.^[2]

- **Increased Temperatures:** Rising global temperatures directly affect bridge materials. Prolonged exposure to higher temperatures can lead to thermal expansion and contraction, causing stress on structural elements. These thermal cycles contribute to the degradation of materials over time, potentially leading to cracking, warping, and reduced load-bearing capacity.

- **Alignment and Orientation:** The alignment of a bridge as to the prevailing sunlight and wind patterns significantly influences temperature-induced damages. Bridges aligned perpendicular to the path of the sun may experience more severe thermal stresses. Similarly, bridges oriented in a way that exacerbates wind-induced cooling can intensify the temperature-related impacts.

- **Altered Precipitation Patterns:** Changes in precipitation patterns, including increased frequency of intense rainfall or prolonged droughts, impact bridges in diverse ways. Excessive rainfall can lead to flooding, erosion, and scour around bridge foundations, while prolonged droughts may cause soil shrinkage, affecting the stability of bridge supports.

- **Alignment and Orientation:** The alignment and orientation of a bridge as to the dominant rainfall direction play a critical role. Bridges aligned parallel to prevailing rainfall may face increased runoff, leading to higher flood risks. Proper alignment and drainage planning are essential to mitigate these risks.

- **More Frequent and Severe Storms:** Climate change is associated with an increase in the frequency and intensity of storms, including hurricanes, typhoons, and cyclones. These storms subject bridges to powerful winds, heavy rainfall, and storm surges, causing structural damage and accelerating the deterioration process.

- **Alignment and Orientation:** The alignment and orientation of a bridge as to the storm's path significantly affect its vulnerability. Bridges aligned perpendicular to the storm's direction may experience greater wind forces, while those in the direct path may face higher storm surge impacts. Proper alignment and design considerations for extreme weather events are essential.

- **Rising Sea Levels:** The warming climate contributes to the melting of polar ice, resulting in rising sea levels. Coastal bridges are particularly vulnerable, as higher sea levels increase the risk of storm surges, saline intrusion, and corrosive effects on bridge materials.

- **Alignment and Orientation:** Alignment and orientation of the coastal bridges must anticipate rising sea levels. Proper elevation, foundation design, and use of corrosion-resistant materials become critical factors in ensuring the longevity of bridges in these vulnerable areas.

ii. **Aligning Resilience with Changing Hazards:**

The alignment and orientation of bridges play a crucial role in determining their resilience to climate change-induced hazards. To enhance this alignment and build climate-resilient bridges, several key steps and considerations are essential:

- **Climate-Resilient Design:** Incorporating climate-resilient design principles is paramount. This includes considering the specific climate hazards prevalent in the region, aligning the bridge to minimize exposure to extreme temperatures and winds, and incorporating materials that can withstand changing environmental conditions.
- **Site-Specific Assessments:** Conducting thorough site-specific assessments is crucial for understanding the unique climate risks faced by a bridge. This includes analysing local weather patterns, historical climate data, and future climate projections. Site-specific assessments guide alignment decisions and adaptation strategies.
- **Adaptive Maintenance Practices:** Implementing adaptive maintenance practices is essential for ongoing resilience. Regular inspections, monitoring of climate-related stresses, and timely repairs or retrofits based on changing conditions contribute to the prolonged functionality of the bridge.
- **Community Engagement:** Involving local communities in the decision-making process fosters a holistic approach to climate resilience. Community insights can provide valuable information about historical climate impacts, traditional knowledge, and localized vulnerabilities that may not be apparent through technical assessments alone.

In conclusion, the impact of climate change on bridge infrastructure is multifaceted, encompassing diverse hazards that necessitate adaptive engineering and maintenance strategies. The alignment and orientation of bridges emerge as critical factors in determining their vulnerability to changing climate conditions. By aligning resilience measures with the specific hazards faced and incorporating climate-resilient design principles, it is possible to mitigate the impacts of climate change on bridges and ensure their sustained functionality in the face of evolving environmental challenges.

iii. **Bridge design to counter the climate change hazard:**

Climate change poses significant challenges to infrastructure worldwide, and bridges, as critical components of transportation networks are particularly vulnerable to its impacts. Designers play a crucial role in developing structures that not only withstand the current effects of climate change but also anticipate and adapt to future challenges. This narrative explores the various elements that designers incorporate into bridge design to counter the hazards associated with climate change. ^[3]

Understanding Climate Change Hazards:

Climate change introduces a range of hazards that can affect bridge infrastructure, including rising temperatures, increased frequency and intensity of extreme weather events, sea-level rise, and changes in precipitation patterns. These

hazards necessitate a proactive approach in bridge design to enhance resilience and ensure the longevity of these essential structures.

Incorporating Climate-Resilient Features into Bridge Design:

- **Temperature Resilience:** Rising temperatures can influence bridge materials, causing thermal expansion and contraction. To counteract this, designers incorporate materials with high thermal stability and use expansion joints to accommodate temperature-related movements. Additionally, the application of reflective surfaces or coatings mitigates heat absorption and reduces the urban heat island effect in urban areas.
- **Cool Pavements:** Integrating cool pavements in bridge design involves using materials that reflect more sunlight and absorb less heat. This reduces surface temperatures, minimizing the impact of high temperatures on the structural elements of the bridge.

Extreme Weather Preparedness: Design of bridges must withstand the increasing frequency and intensity of extreme weather events, including storms, hurricanes, and heavy rainfall. Designers incorporate aerodynamic shapes and wind-resistant features to counteract strong winds. Robust and integrated drainage systems manage heavy rainfall and prevent flooding.

- **Aerodynamic Designs:** Aerodynamic considerations are critical, especially in areas prone to hurricanes or strong winds. Engineers design bridges with shapes that minimize wind resistance, reducing the dynamic forces exerted on the structure during storms.
- **Enhanced Drainage Systems:** Climate change often leads to more intense and erratic rainfall. Incorporation of enhanced drainage systems, including larger culverts and efficient storm-water management, prevent water accumulation and flooding, which can compromise the structural integrity of bridges.

Sea-Level Rise Adaptation: Coastal bridges face the additional challenge of rising sea levels. Designers anticipate future sea-level rise by elevating bridge foundations, using corrosion-resistant materials and incorporating flexible designs that can adapt to changing water levels.

- **Elevation of Foundations:** Anticipating sea-level rise involves elevating bridge foundations to ensure that the structure remains above water levels. This proactive measure minimizes the risk of inundation and saltwater exposure, enhancing the longevity of the bridge.
- **Corrosion-Resistant Materials:** The use of corrosion-resistant materials, such as stainless steel or specially coated alloys, helps protect bridge components from the corrosive effects of saltwater. This is particularly crucial for coastal bridges facing the dual challenge of sea-level rise and saltwater exposure.

Flexibility and Adaptability: Climate-resilient bridge design emphasizes flexibility and adaptability. This includes the use of materials that can withstand a range of environmental conditions and the incorporation of smart technologies for real-time monitoring and early detection of potential issues.

- **Structural Health Monitoring:** Implementing structural health monitoring systems allows designers to assess the real-time performance of a bridge. Early detection of any deviations from expected condition enables prompt intervention and maintenance to prevent further damage.

Steps in Climate-Resilient Bridge Design:

- **Comprehensive Risk Assessment:** The first step in climate-resilient bridge design is a comprehensive risk assessment. Designers evaluate the specific climate hazards the bridge may face, considering factors such as location, climate projections, and historical weather patterns.
- **Integration of Climate Data:** Incorporating current and projected climate data into the design process ensures that bridges are prepared for future conditions. This includes considering changes in temperature, precipitation, sea levels, and the frequency of extreme weather events.
- **Collaboration with Climate Scientists:** Collaboration with climate scientists is essential for obtaining accurate and up-to-date information on climate change impacts. Engaging in interdisciplinary collaboration integrates the latest scientific insights into the design process.
- **Public Engagement and Community Input:** Climate-resilient bridge design involves engaging with the local community to gather insights into their experiences and concerns. This collaborative approach ensures that the design meets the needs of the community and enhances overall resilience.

In conclusion, climate change presents unprecedented challenges to bridge infrastructure, requiring innovative and proactive solutions from designers. By understanding and incorporating climate-resilient features, designers can create bridges that not only withstand the current impacts of climate change but also adapt to future uncertainties. From temperature-resilient materials to flexible designs and advanced monitoring technologies, each element plays a crucial role in ensuring the longevity and functionality of bridges in a changing climate. This holistic approach not only safeguards critical infrastructure but also contributes to sustainable and resilient communities.

iv. Retrofitting and Strengthening Technologies for Countering the Impact of Climate Change Hazard

Climate change poses a growing threat to the stability and functionality of infrastructure, including bridges. To address the evolving challenges brought about by climate-related hazards, retrofitting and strengthening technologies have emerged as vital components of bridge resilience strategies. This narrative explores the various retrofitting and strengthening technologies employed to counter the impact of climate change hazards on bridges.

Understanding the Climate Change Hazard:

Climate change introduces a range of hazards, including extreme weather events, rising temperatures, sea-level rise, and an increase in precipitation. These hazards can have profound effects on bridge infrastructure, necessitating adaptive measures to enhance resilience and ensure the continued functionality of these critical structures.

Retrofitting Technologies:

Retrofitting involves the modification or addition of components to existing bridge structures to enhance their performance and ability to withstand the impacts of climate change. Several retrofitting technologies address specific vulnerabilities associated with climate-related hazards:

Seismic Retrofitting: As climate change results in an increase in the frequency and intensity of earthquakes, seismic retrofitting becomes crucial. This involves reinforcing bridge components to improve their resistance to seismic forces. Techniques include the installation of base isolators, dampers, and the strengthening of structural elements to minimize damage during earthquakes.

- **Base Isolators:** Base isolators are devices placed between a structure's foundation and superstructure. They allow the structure to move independently of the ground motion during an earthquake, reducing the transmission of seismic forces and minimizing structural damage.
- **Dampers:** Dampers, such as tuned mass dampers or viscous dampers, absorb and dissipate energy during seismic events. They are effective in reducing the amplitude of vibrations and enhancing the seismic resilience of the bridge.

Corrosion-Resistant Coatings: Coastal and humid environments, exacerbated by climate change, contribute to the corrosion of bridge materials. Retrofitting with corrosion-resistant coatings, such as epoxy or zinc-based coatings protects bridge components from the corrosive effects of saltwater, increasing the longevity of the structure.

- **Cathodic Protection Systems:** Cathodic protection involves the installation of sacrificial anodes or impressed current systems to prevent corrosion. Sacrificial anodes corrode in place of the bridge components, providing an additional layer of protection against the corrosive impact of saltwater.

Temperature-Resilient Materials: Rising temperatures can lead to thermal expansion and contraction, affecting the integrity of bridge materials. Retrofitting with temperature-resilient materials, such as high-performance concrete or fibre-reinforced polymers, helps counteract the negative effects of temperature variations.

- **Fibre-Reinforced Polymers (FRP):** FRP materials are lightweight and resistant to corrosion and temperature variations. Retrofitting with FRP composites provides additional strength to bridge components and enhances their durability under changing climate conditions.

Strengthening Technologies:

Strengthening technologies involve reinforcing existing bridge elements to improve their load-carrying capacity and overall resilience. Technologies help address the climate-related hazards exacerbated vulnerabilities.

Adding Reinforcements: Strengthening bridges often involves adding reinforcements to key structural elements. This may include adding steel plates or external post-tensioning to enhance the capacity of beams, columns, or bridge decks.

- **Carbon Fibre Reinforcements:** Strengthening of bridges results from the use of lightweight, high strength material like Carbon fibre reinforcements. These reinforcements are particularly effective in enhancing the flexural and shear capacity of structural elements.

Upgrading Foundations: Changes in precipitation patterns and increased likelihood of flooding require the upgrading of bridge foundations to withstand the impacts of climate-related hazards. This may involve deepening foundations, adding scour protection, or implementing innovative foundation designs.

- **Scour Protection Measures:** Scour protection involves the installation of measures to prevent the erosion of soil around bridge foundations. This may include riprap, gabions, or other erosion-resistant materials to safeguard the stability of the foundation.
- **Enhanced Drainage Systems:** Increased precipitation, a common consequence of climate change, necessitates the enhancement of drainage systems to manage water runoff effectively. Strengthening bridges includes the implementation of larger culverts, improved stormwater management, and efficient drainage channels.
- **Sustainable Drainage Systems (SuDS):** SuDS involves the use of natural or artificial methods to manage surface water runoff. These systems promote sustainable and environmentally friendly drainage, reducing the risk of flooding and erosion around bridge structures.

Integration of Retrofitting and Strengthening Technologies:

The effective enhancement of bridge resilience to climate change hazards often involves the integrated use of retrofitting and strengthening technologies. This holistic approach considers the specific vulnerabilities of each bridge and tailors solutions to address multiple climate-related challenges simultaneously.

Challenges and Considerations:

While retrofitting and strengthening technologies offer effective solutions, their implementation comes with challenges. Considerations include cost implications, potential disruptions to traffic flow during retrofitting activities, and the need for ongoing maintenance to ensure the continued effectiveness of these measures.

Retrofitting and strengthening technologies play a pivotal role in countering the impact of climate change hazards on bridges. By incorporating these technologies, engineers can adapt existing structures to the evolving challenges posed by rising temperatures, extreme weather events, and other climate-related factors. The integration of climate-resilient materials, seismic retrofitting techniques, and enhanced drainage systems contributes to the creation of bridges that not only withstand current climate challenges but also provide sustainable and resilient infrastructure for the future.

v. Case studies of climate-resilient bridge design

Examining case studies of climate-resilient bridge design can provide valuable insights into successful approaches and innovative solutions for addressing natural hazards and climate change. Here are a few noteworthy examples:



Fort McHenry Tunnel, Maryland: This tunnel, which connects Baltimore with its eastern suburbs, retrofitted with a floodwall to protect against sea-level rise and storm surges. By implementing this flood protection measure, the tunnel remains operational even during extreme weather events. The Fort McHenry Tunnel displays innovative engineering to address climate challenges in a coastal urban environment.

Evergreen Point Floating Bridge, Washington: Located in Seattle, Washington, the Evergreen Point Floating Bridge built to adapt to the changing water levels of Lake Washington. In the Pacific Northwest, the region experiences fluctuations in water levels due to climate change and seasonal variations. The bridge's floating design allows it to adjust to these changing conditions while maintaining its structural integrity and functionality.



The importance of establishing resilience in bridges considering natural hazards risk cannot be overstated. Climate change and extreme weather events pose significant challenges to bridge infrastructure, and addressing these challenges is essential to maintain the safety and functionality of transportation networks. Strategies such as adapting bridges to temperature fluctuations, increased precipitation, and sea-level rise, as well as reinforcing materials and enhancing wind resistance, play a vital role in ensuring climate resilience.

Case studies of climate-resilient bridge design demonstrate that innovative engineering solutions can effectively address the challenges posed by natural hazards. By drawing inspiration from these examples and implementing comprehensive resilience strategies, bridge engineers and managers can contribute to the long-term sustainability and safety of critical transportation infrastructure. Ultimately, the field of bridge engineering must continue to evolve and adapt to the changing climate and the increasing risks associated with natural hazards, fostering a more resilient and secure future for bridge infrastructure worldwide.

vi. Early Warning Systems: A Proactive Approach:

Definition and Components: Early warning systems refer to a set of coordinated processes, tools, and communication strategies designed to inform individuals, communities, and authorities about imminent or potential climate-related hazards. These systems typically involve monitoring, forecasting, dissemination of information, and community engagement.

Key Components of Early Warning Systems ^[4]:

- **Monitoring and Data Collection:** Early warning systems rely on continuous monitoring and data collection from various sources, including meteorological stations, satellite imagery, and climate sensors. This data provides the foundation for accurate hazard assessments.
- **Forecasting and Modelling:** Meteorological agencies and climate scientist's use advanced forecasting models to predict the occurrence and intensity of climate-related hazards. These models consider historical data, climate patterns, and real-time observations to generate reliable forecasts.
- **Risk Assessment and Mapping:** Risk assessments evaluate the potential impact of climate-related hazards on specific regions. Mapping tools identify vulnerable areas and help prioritize resource allocation for preparedness and response measures.
- **Communication and Alert Systems:** Effective communication is a cornerstone of early warning systems. Timely alerts and warnings disseminated through various channels, including traditional media, mobile applications, sirens, and community networks help community.
- **Community Engagement and Education:** Community involvement is crucial for the success of early warning systems. Engaging communities through education programs, drills, and outreach activities enhances awareness and ensures a coordinated response.

Early Warning Signs for Climate Change Hazards: Recognizing the Indicators:

Extreme Weather Events:

- **Early Warning Signs:** Unusual weather patterns, such as unexpected heatwaves, intense storms, or prolonged periods of rainfall, can serve as early warning signs for potential climate-related hazards. Anomalous weather events that deviate from historical norms may indicate evolving climate conditions.
- **Response Measures:** Monitoring weather forecasts and recognizing deviations from typical weather patterns allow authorities to implement proactive measures, such as evacuation plans, flood defences, or heatwave response strategies.

Sea-Level Rise:

- **Early Warning Signs:** Unexplained tidal variations, coastal erosion, or frequent flooding in low-lying areas are early warning signs of potential sea-level rise. Changes in shoreline patterns and saltwater intrusion into freshwater sources are additional indicators.
- **Response Measures:** Coastal communities can implement early warning systems that monitor sea-level changes. Infrastructure improvements, such as seawalls or elevated platforms, planned to mitigate the impact of rising sea levels.

Shifts in Precipitation Patterns:

- **Early Warning Signs:** Changes in precipitation patterns, including irregular rainfall, drought conditions, or unexpected heavy rainfall, can be early warning signs for potential floods, landslides, or water scarcity.
- **Response Measures:** Developing water management strategies, implementing water conservation measures during droughts, and enhancing flood defences based on shifting precipitation patterns are essential response measures.

Temperature Extremes:

- **Early Warning Signs:** Unprecedented temperature extremes, such as prolonged heatwaves or unusually cold spells, can indicate climate-related hazards. Anomalies in seasonal temperatures may influence ecosystems, agriculture, and human health.
- **Response Measures:** Early warning signs related to temperature extremes prompt the development of heatwave response plans, agricultural adaptations, and public health campaigns to mitigate the impact on vulnerable populations.

Challenges and Opportunities in Early Warning Systems:

Challenges:

- **Limited Infrastructure:** Some regions, especially in developing countries, may lack the necessary infrastructure for comprehensive early warning systems, limiting their ability to provide timely alerts.
- **Data Accuracy and Availability:** The accuracy and availability of real-time data can be a challenge, particularly in remote areas or regions with limited access to monitoring technologies.
- **Community Engagement:** Ensuring active community participation and understanding of early warning messages can be challenging. Language barriers, cultural differences, and varying levels of literacy may affect the effectiveness of communication.

Opportunities:

- **Advancements in Technology:** Technological advancements, including satellite technology, climate modelling, and communication tools, offer opportunities to enhance the accuracy and reach of early warning systems.
- **International Collaboration:** Collaboration between countries and international organizations can facilitate the exchange of expertise, resources, and best practices in developing and implementing effective early warning systems.
- **Community-Based Initiatives:** Empowering and participating local communities in early warning systems can improve the effectiveness of alerts and enhance community resilience.

Under UNDRR, focus is to increase the depth and reach of early warning systems to the most affected communities and to those who are most vulnerable to the impact of the hazards.

The Sendai Framework adopted in Sendai, Japan in 2015 includes four priorities:

- Understanding disaster risk.
- Strengthening disaster risk governance to manage disaster risk.
- Investing in disaster risk reduction for resilience.
- Enhancing disaster preparedness for effective response and to "Build Back Better" in recovery, rehabilitation, and reconstruction.

Accordingly, UNDRR has given importance to risk knowledge; technical monitoring and warning service; communication and dissemination of warnings; and community response capability. UNDRR focuses on the "Early Warnings for All" initiative is a ground-breaking effort to ensure everyone on Earth is protected from hazardous weather, water, or climate events through life-saving early warning systems by the end of 2027.

In conclusion, early warning systems and the recognition of early warning signs are integral components of climate resilience efforts. As climate change continues to reshape the frequency and intensity of hazards, the proactive nature of early warning systems becomes increasingly crucial. By leveraging advanced technologies, fostering community engagement, and addressing challenges, early warning systems can play a pivotal role in minimizing the impact of climate-related hazards and building resilient communities prepared for the unpredictable challenges of a changing climate.

D) SEISMIC/EARTHQUAKE RESILIENCE:

a) Climate resilience and seismic resilience are critical aspects of bridge engineering, addressing the challenges of a changing environment and the ever-present threat of seismic events to ensure the safety and functionality of vital transportation infrastructure. Seismic or earthquake resilience stands as a testament to a bridge's intrinsic capability not only to withstand but also to rebound from the devastating forces unleashed by seismic events, foremost among them being earthquakes. This resilience comprises a multifaceted approach, entailing intricate engineering and design practices, meticulously arranged to endow bridges with the profound capacity to defy the tragic consequences of ground shaking, ground deformation, and an array of seismic aftershocks, all the while avoiding the specter of tragic damage. At its core, seismic resilience transcends the boundaries of initial construction, extending to the renewal of aging bridges, aligning them with contemporary seismic standards and, in a forward-looking stance, premeditating post-earthquake recovery endeavors, all aimed at minimizing operational downtime and assuring the continued serviceability of these vital lifelines.^[5]

b) Impact of the hazard on bridges:

Earthquakes pose a significant threat to the structural integrity of bridges, often resulting in various forms of damage that can compromise safety and functionality. The impact and severity of damage depend on multiple factors, including the alignment and orientation of the bridge. This discussion explores the typical impact of earthquake hazards on bridges and elucidates how the alignment and orientation significantly influence the severity of the damage.^[6]



Typical Impact of Earthquake Hazards on Bridges:

- **Foundation Vulnerability:** One of the primary areas of impact during an earthquake is the foundation of the bridge. The ground motion generated by seismic activity can lead to soil liquefaction, where the soil temporarily loses its strength and behaves like a liquid. This phenomenon undermines the support provided by the foundation, increasing the risk of settlement, or tilting of the bridge supports.
- **Lateral Forces on Piers and Abutments:** The lateral forces exerted during an earthquake pose a substantial risk to bridge piers and abutments. Depending on the intensity of the seismic activity, these lateral forces can cause misalignment, tilting, or even collapse of bridge supports. Factors, which influence the vulnerability of these components, are bridge's design, materials used, and the characteristics of the underlying soil.
- **Superstructure Damage:** The superstructure, comprising the bridge deck, girders, and other elements above the supports, is also susceptible to earthquake-induced damage. Seismic forces can lead to cracking, warping, and displacement of the bridge deck. In severe cases, these damages may compromise the overall stability and load-bearing capacity of the bridge.
- **Dynamic Stresses on Materials:** The dynamic nature of earthquake forces subjects bridge materials to stress beyond their static load-bearing capacity. This repeated stress can lead to fatigue in structural components, weakening the materials over time. Fatigue-induced damage may not be immediately apparent but can contribute to long-term deterioration and necessitate extensive maintenance and rehabilitation efforts.

Alignment of the bridges and the Impact of alignment on bridge resilience for earthquake hazards:

Few factors that influence the bridges most apart from the magnitude of the seismic forces include alignment of the bridge. Alignment plays a crucial role in determining the resilience of bridges during earthquakes. A properly aligned bridge, designed to withstand seismic forces, can significantly reduce the risk of damage and enhance overall seismic resilience. Strategic alignment considerations involve ensuring the bridge's geometry and foundation design account for potential ground movements, minimizing the impact of seismic forces

on structural components. Additionally, proper alignment helps distribute loads efficiently, preventing concentrated stress points that might otherwise lead to structural failure during an earthquake. Bridge alignment refers to the geometric configuration of a bridge, including its horizontal and vertical alignment.^[7] The alignment of a bridge is a critical factor in determining its resilience to various hazards, including earthquakes.

Parallel or Perpendicular to Fault Lines:

- Bridges aligned parallel or perpendicular to fault lines may experience different levels of ground motion during an earthquake.
- Proper alignment with fault lines can reduce the seismic forces exerted on the bridge, enhancing its resilience.

Bridge Configurations:

- The alignment affects the bridge's dynamic response during an earthquake. Straight alignments may experience less torsional motion, while curved alignments may distribute seismic forces more evenly.

Curvature and Flexibility:

- Curved alignments can distribute seismic forces more evenly, reducing concentrated stress points.
- Flexible alignments with gradual transitions between curves and straight segments can enhance seismic resilience by allowing the bridge to move more freely during an earthquake.

Foundation Considerations:

- Proper foundation design, considering soil conditions and seismic activity, is crucial for earthquake resilience.
- Bridge alignment should account for potential differential movements of foundations during an earthquake.

c) Bridge design to counter the hazard.

Earthquake engineering and bridge design represent the cutting edge of structural engineering, focusing on the art and science of creating bridges that can withstand the turbulent forces generated by seismic activity. This artistry encompasses a symphony of innovations, such as designing foundations with unparalleled flexibility, harnessing the power of base isolators, and the judicious selection of materials that can withstand lateral forces. The core tenet of seismic design revolves around the regional assessment of specific earthquake risks, with a keen eye on the unpredictable nature of the land beneath.

Earthquake Engineering and Bridge Design: Earthquake engineering is a specialized field that focuses on designing structures, including bridges, to withstand the forces generated by seismic events, such as earthquakes. The challenges and considerations in earthquake engineering are unique and demand innovative approaches to ensure structural safety and integrity. ^[8]



Base Isolators: Base isolators are devices that play a pivotal role in earthquake-resilient bridge design. They are instrumental in decoupling the bridge from the ground motion during an earthquake. These devices absorb and dissipate seismic energy, reducing the forces transmitted to the bridge structure. Details of base isolators are as under:

- **Decoupling the Bridge:** The primary function of base isolators is to decouple the bridge from the ground motion. They allow the bridge to move independently of the shaking ground, effectively isolating it from the seismic forces. This decoupling minimizes the transmission of potentially destructive forces to the bridge, preserving its structural integrity.
- **Absorbing Seismic Energy:** Designed Base isolators absorb and dissipate seismic energy. They act as shock absorbers for the bridge, converting and dissipating the kinetic energy generated by the earthquake. By doing so, they reduce the amplitude and impact of the ground motion on the bridge.
- **Protecting Against Structural Damage:** The use of base isolators significantly reduces the risk of structural damage to the bridge during an earthquake. This technology allows the bridge to ride out seismic events with minimal deformation or harm, ensuring that it remains safe and functional even after a major earthquake.

Flexible Foundations: The resilience of earthquake-resistant bridges lies in their foundations; designed meticulously to be pliable and dynamic. This unique flexibility allows the bridge to respond to seismic motion with grace, accommodating ground movement without succumbing to structural deformation or damage. Key aspects of flexible foundations are as under:

- **Pliability and Dynamic Response:** Engineered Flexible foundations are pliable and responsive to ground motion. Their design enables them to absorb and dissipate seismic energy, allowing the bridge to move with the shaking ground without sustaining significant damage. This dynamic response helps protect the integrity of the bridge.
- **Mitigating Structural Deformation:** The flexibility of the foundation helps mitigate structural deformation during an earthquake. Instead of resisting seismic forces rigidly, which can lead to damage, the flexible foundation allows controlled movement that prevents structural harm.

- **Enhancing Structural Resilience:** Flexible foundations are a cornerstone of earthquake resilience in bridge design. They enable the bridge to withstand the unpredictable and violent forces of an earthquake while maintaining its functionality. This resilience is essential for ensuring the safety of bridge users and the continuity of transportation networks.

Ductile Materials: The selection of materials for bridge construction is a critical aspect of earthquake-resistant design. Wise material choices can significantly enhance a bridge's ability to withstand seismic forces. Ductile materials, in particular, play a pivotal role in earthquake resilience:

- **Flexibility and Absorption of Energy:** Ductile materials have flexibility and the ability to absorb seismic energy. During an earthquake, these materials can bend and deform without breaking or shattering. This characteristic allows them to dissipate the earthquake's energy, protecting the structural integrity of the bridge.
- **Preventing Brittle Failure:** The use of ductile materials helps prevent brittle failure in the bridge structure. Brittle materials may fracture when subjected to seismic forces, leading to catastrophic failure. Ductile materials, on the other hand, exhibit controlled deformation and are better equipped to withstand the dynamic forces of an earthquake.
- **Enhancing Structural Robustness:** Ductile materials enhance the robustness of the bridge, ensuring that it can endure the unpredictable nature of seismic activity. This robustness is a critical aspect of earthquake resilience, as it allows the bridge to continue serving its transportation function even after an earthquake.

Earthquake Engineering and Bridge Design represent an intricate and evolving field that addresses the unique challenges posed by seismic activity. Base isolators, flexible foundations, and ductile materials are key elements in earthquake-resilient bridge design. These innovations and material choices are essential for ensuring the safety of bridge infrastructure and its ability to withstand the unpredictable forces of earthquakes while preserving its functionality and structural integrity.

d) Seismic retrofitting and strengthening of bridges:

In an era where the history of bridges faces the challenge of compliance with contemporary seismic exigencies, seismic retrofitting emerges as a grand renovation. Seismic retrofitting and strengthening of bridges are crucial processes aimed at enhancing the earthquake resilience of existing bridge structures. These strategies involve the implementation of various engineering measures to retrofit bridges and prepare them for seismic events.



Some key components of seismic retrofitting include the addition of lateral bracing to increase a bridge's ability to withstand horizontal ground motion, fortifying bridge piers and abutments to prevent damage or collapse during an earthquake, and elevating bridge foundations to reduce the risk of settlement or tilting. These retrofits are essential because many designed older bridges could not withstand the seismic forces that modern engineering standards require. By undertaking seismic retrofitting and strengthening, bridges can better endure the potentially destructive impact of earthquakes, ensuring their continued functionality and the safety of the people who use them.

- **Lateral Bracing:** It measures to enhance the structural integrity of bridges and their ability to withstand seismic forces, which are movements generated by earthquakes. One key method is "Lateral Bracing," which involves reinforcing bridge components to resist lateral forces that can occur during an earthquake. Lateral bracing adds additional support to bridge elements, making them more resilient to side-to-side movement. This retrofitting technique helps prevent structural damage and maintain the bridge's functionality during and after an earthquake, ultimately contributing to improved safety and disaster resilience in regions prone to seismic activity.
- **Bridge Piers and Abutments:** Seismic retrofitting and strengthening of bridges are crucial engineering practices aimed at enhancing a bridge's ability to withstand the forces generated by seismic disturbances, such as earthquakes. This involves reinforcing bridge piers (vertical supports) and abutments (end supports) to make them more robust and resistant to seismic forces. One common method is the installation of steel jackets or fiber-reinforced polymers around these structural components. These materials provide additional strength and flexibility, reducing the risk of structural damage or collapse during an earthquake. Retrofitting and strengthening bridges, significantly improves the overall resilience to seismic events, ensuring the safety of transportation infrastructure and public safety in earthquake-prone regions.
- **Foundation Upgrades:** Seismic retrofitting and strengthening of bridges refer to engineering measures taken to enhance the earthquake resistance of existing bridge structures. Foundation upgrades, a crucial aspect of seismic retrofitting, involve reinforcing or improving the bridge's base to withstand the lateral forces and ground motion generated by seismic events. This may include adding additional piles, deepening foundations, or using advanced materials to

increase the foundation's capacity to resist seismic forces. Strengthening bridge foundations is vital as it helps prevent settlement, tilting, or structural damage during an earthquake, ultimately ensuring the safety and functionality of the bridge in the event of a seismic event. These retrofitting measures are essential for protecting critical infrastructure and public safety in earthquake-prone regions.

Post-earthquake bridge recovery strategies.

Post-earthquake bridges will need strategies that cater to the immediate and prompt reinstatement of bridges to ensure relief and rescue services can reach the affected zone and ensure safety of lives. Studies to date have revealed that bridges in corrosion-prone areas are most susceptible to seismic waves and force. This increased susceptibility arises due to the type of deterioration that results from corrosion among other causes. Studies highlight the fact that the performance of the bridge more specifically the ductility decreases over the service life due to the impact of corrosion. It is critical to understand the combined effect on the bridge, which is deteriorated due to corrosion and likely to experience the impact of earthquake.

Most of the studies have identified that bridges that are in corrosion-prone areas are most vulnerable to severe distress leading to failure when seismic waves and forces influence it. An exhaustive and detailed study is essential to identify the primary and secondary distress occurring in the bridge. Primary distress is distress caused by seismic waves and forces. When seismic waves and forces are the primary cause, distress is termed primary distress. Whereas when the distress amplified during earthquake / seismic waves and forces resulting from previous structural distress or partial failure is termed Secondary distress. Secondary distress results from the realignment of stress and strains. Initial design of the bridge does not account for such stress and strains.

Many factors contribute to the performance of the bridge during and post-earthquake. Previous studies have identified a few predominant factors.

- **The site location** of the bridge is one factor that affects the response of the bridge to seismic forces. The geology of the location is the principle-influencing factor. Deep soft soil amplifies the ground movement and causes severe damage as was seen during the earthquake in California and Japan. Another factor contributing to long-term impact is the possibility of the soil undergoing liquefaction.
- **Design philosophy:** The period in which the bridge is constructed defines the type of damage that the bridge will undergo. This stems from the basic design philosophy. Older bridges would face more severe damage to earthquakes if the designs had not included the provisions of earthquake evaluation. No provision of stringent detailing for earthquakes and assuming lower design forces in the past provide an ideal situation for seismic distress to be severe. Another contributory factor is the variations introduced during the design and construction phase. Designs that enable inelastic energy dissipation are designs that will witness the least severe distress.
- **Expansion joints distress and geometry of bridge:** The joints, which are normal and routinely provided to dissipate volume change and temperature stress, can introduce irregularity, which can influence in a catastrophic manner.

This irregularity arises when the joints are unseated. Unseating of joints is more common when the seat provided in older construction is short. Sort seats make it feasible for the two adjoining segments to be unseated during seismic waves and forces. Bridges in California, which had short seats and or had simply supported beams faced catastrophic distress. Providing hinged restrainers during original construction has resulted in the avoidance of unseating short-seat bridges. Bridges with skewed alignment or curvature show more distress during earthquakes.

- **Distress in Bridge structure:** The superstructure of the bridge provides the much-required elasticity for easy dissipation during the occurrence of seismic waves. This forms the basic framework for resistance against seismic forces. A superstructure that is in distress will be ineffective in providing resistance. However past studies have also highlighted the fact that superstructure distress rarely has caused total collapse. The distress in substructure and the damage in bearing have influenced the collapse or the failure of bridges during seismic activity in the past. Such distress in the substructure and bearings have resulted in the failure of the superstructure, which resulted in the failure of the deck. Bearings normally provide for the movement of the superstructure in one particular direction only. Failure of these bearings during seismic activity can result in a redistribution of stress causing the failure of superstructure/substructure due to overloading.

e) **Lessons from Historic Seismic/Earthquake and Case Studies:**

Historic seismic events have played a pivotal role in shaping seismic resilience in bridge engineering. These lessons stem from the examination of past earthquakes and their impacts on bridges, providing valuable insights that have informed the development of modern seismic design principles and retrofitting techniques. The primary lessons include the need for robust seismic design standards, innovative engineering solutions, and proactive measures to enhance the safety and resilience of bridges in earthquake-prone regions. The impact of learning from historic seismic events has been significant in terms of reducing the vulnerability of bridges and ensuring the safety of transportation networks. By incorporating these lessons into bridge design and retrofitting practices, engineers have been able to create structures that can better withstand the forces of earthquakes and recover more swiftly from their aftermath. This, in turn, has led to increased public safety and reduced economic losses associated with seismic events.

Case Study: Corrosion Distress in Earthquake-Affected Bridges:

In earthquake-prone regions, the intersection of seismic activity and corrosion distress poses a unique challenge to the structural integrity of bridges. A compelling case study that exemplifies the impact of corrosion distress in the aftermath of an earthquake is the Hanshin Expressway in Kobe, Japan, following the devastating Great Hanshin Earthquake of 1995.

- **Background:** The Great Hanshin Earthquake, also known as the Kobe earthquake, struck the Hyogo Prefecture on January 17, 1995, with a magnitude of 6.9. Among the critical pieces of infrastructure affected was the Hanshin Expressway, a vital transportation artery in the region



- **Corrosion Distress Impact:** The earthquake-induced shaking not only inflicted immediate damage but also initiated a latent threat—corrosion. The seismic activity compromised the protective coatings on the bridge's steel components, exposing them to corrosive elements such as moisture and salt. The Hanshin Expressway, being in proximity to the coastal area, was especially susceptible to the corrosive effects of saltwater.
- **Delayed Consequences:** While the earthquake garnered immediate attention for its visible impact on the Hanshin Expressway, the insidious effects of corrosion became apparent over time. The compromised steel components, now vulnerable to corrosion, experienced a gradual deterioration of their structural integrity.
- **Increased Vulnerability during Aftershocks:** Subsequent aftershocks, common in the aftermath of a major earthquake, further accelerated the corrosion process. The compromised structural elements, weakened by both seismic activity and corrosion, became more susceptible to the dynamic forces induced by aftershocks.
- **Impact on Structural Stability:** The combined effects of seismic damage and corrosion distress led to a decline in the structural stability of the Hanshin Expressway. The corroded steel components lost their load-bearing capacity, compromising the overall integrity of the bridge. This deterioration became a critical concern for public safety and transportation functionality.
- **Mitigation Measures:** Recognizing the imminent threat posed by corrosion, extensive retrofitting efforts initiated to address the deteriorating condition of the Hanshin Expressway. These measures included the removal and replacement of corroded steel elements, the application of advanced corrosion-resistant coatings, and the implementation of a comprehensive corrosion monitoring system.
- **Lesson Learned:** The case of the Hanshin Expressway underscores the importance of addressing not only the immediate seismic damage but also the latent threat of corrosion in earthquake-prone regions. It emphasizes the need for proactive measures to protect bridge infrastructure from the long-term

consequences of corrosion, especially when exposed to corrosive elements such as saltwater in coastal areas.

The intersection of seismic events and corrosion distress, as exemplified by the Hanshin Expressway case study, highlights the complex challenges faced by earthquake-prone regions. It reinforces the necessity for a holistic approach to bridge resilience, considering both immediate seismic impact and the long-term effects of corrosion. Incorporating corrosion-resistant materials, robust protective coatings, and proactive monitoring systems emerge as essential strategies to enhance the durability and safety of bridges in seismic zones. The lessons learned from this case study contribute to the ongoing efforts to fortify infrastructure against the dual threats of earthquakes and corrosion.

Case Study: Loma Prieta Earthquake (1989):

- **Lesson:** The Loma Prieta Earthquake emphasized the need for retrofitting existing bridges, particularly the reinforcement of bridge piers and abutments, to enhance their seismic resilience.
- **Impact:** Retrofitting measures, such as strengthening piers and abutments, applied to numerous bridges, significantly improve their ability to withstand seismic forces and reducing the risk of collapse during earthquakes.

These case studies illustrate the lessons learned from historic seismic events and their tangible impact on improving the seismic resilience of bridges. By applying these lessons, engineers and agencies have made significant strides in enhancing the safety and functionality of critical infrastructure in earthquake-prone regions.

Case Study: The Northridge Earthquake (1994):



- **Lesson:** The Northridge Earthquake highlighted the importance of flexible foundations and the use of base isolators in bridge design to minimize damage during seismic events.
- **Impact:** Incorporating flexible foundations and base isolators in subsequent bridge projects significantly increased their seismic resilience, reducing the risk of catastrophic damage and ensuring continued functionality.

f) **Early warning system and early warning signs for the hazard**

UNDRR's session in 2015 Paris "International Platform for Earthquake Early Warning System (IP-EEWS) provides a platform for the open sharing of knowledge and expertise between public and government agency to contribute to the creation and operation of early warning systems in hazard-prone areas, including in developing countries. Earthquakes are critical as over 80% of disasters around the world are climate-related and earthquakes contribute to over 70 percent of deaths reported due to disasters.^[22]

Earthquakes, as sudden and unpredictable natural phenomena, present unique challenges for communities and infrastructure. Developing effective early warning systems (EWS) and recognizing early warning signs are crucial components in minimizing the impact of earthquake hazards. This discussion delves into the significance of early warning systems and the identification of early warning signs to enhance preparedness for seismic events.

Understanding the Earthquake Hazard:

Earthquakes result from the sudden release of energy in the Earth's crust, leading to the generation of seismic waves. The impact of earthquakes can range from minor tremors to devastating events, causing structural damage, ground shaking, and potential tsunamis. Early warning systems aim to provide timely information to mitigate the effects of these hazards.

Early Warning Systems: A Proactive Approach:

Definition and Components: Early warning systems for earthquakes involve a coordinated set of processes and technologies designed to detect seismic activity, assess its potential impact, and communicate warnings to at-risk communities. The key components of EWS include seismometers, data analysis algorithms, communication networks, and public alert mechanisms.

- **Seismic Monitoring:** Seismometers strategically placed devices, detect ground motion associated with seismic events. A network of seismometers continuously monitors seismic activity, providing real-time data for analysis.
- **Data Analysis and Warning Issuance:** Advanced algorithms analyse the data collected by seismometers to determine the magnitude, location, and depth of earthquakes. Based on this analysis, warnings issued to relevant authorities and the public, aiming to provide sufficient lead-time for preparedness measures.
- **Communication Channels:** Effective communication is critical in the success of early warning systems. Warnings disseminated through various channels, including emergency alert systems, mobile apps, sirens, and mass media. Ensuring a rapid and reliable flow of information is essential for timely responses.
- **Community Preparedness:** Public awareness campaigns and community education initiatives play a vital role in ensuring that individuals and communities informed about earthquake risks and understand how to respond to early warnings. Conducting drills and providing clear guidelines contribute to community preparedness.

Early Warning Signs for Earthquake Hazards: Recognizing Indicators:

Foreshocks:

- **Early Warning Signs:** Foreshocks are smaller seismic events that precede a larger earthquake. Monitoring and detecting foreshocks can provide an early indication of increased seismic activity in a particular region.
- **Response Measures:** Recognizing foreshocks prompts authorities to activate early warning systems and initiate emergency preparedness measures, including public alerts and evacuation plans.

Animal Behaviour:

- **Early Warning Signs:** Anecdotal evidence suggests that changes in animal behaviour, such as unusual restlessness or agitation in domestic and wild animals, may occur before seismic events.
- **Response Measures:** Unusual animal behaviour, though not a reliable primary indicator, considered as part of a broader approach to earthquake preparedness.

Ground Rupture:

- **Early Warning Signs:** Visible signs of ground rupture or displacement along fault lines may indicate increased seismic stress and the potential for an earthquake.
- **Response Measures:** Monitoring fault lines and recognizing ground rupture early can contribute to hazard assessment and inform land-use planning to minimize the impact on infrastructure.

Changes in Well Water Levels:

- **Early Warning Signs:** Reports of anomalies in well water levels, such as sudden fluctuations or changes, are precursors to seismic activity.
- **Response Measures:** Monitoring well water levels and recognizing unusual changes integrated into comprehensive early warning systems to provide additional data for seismic assessment.

Radon Gas Emissions:

- **Early Warning Signs:** Changes in radon gas emissions from the ground suggested as potential indicators of seismic activity.
- **Response Measures:** Monitoring radon gas levels in specific regions may contribute to early warning efforts, but this method requires further research and validation.

Challenges and Opportunities in Early Warning Systems:

Challenges:

- **False Alarms:** Balancing the need for timely warnings with the risk of false alarms is a significant challenge. False alarms can erode public trust and influence the effectiveness of early warning systems.

- **Global Coverage:** Achieving comprehensive global coverage for early warning systems is challenging, particularly in remote or resource-limited areas.

Opportunities:

- **Advancements in Sensor Technology:** Continuous advancements in sensor technology, including miniaturized and cost-effective seismometers, offer opportunities to expand the coverage and accuracy of early warning systems.
- **International Collaboration:** Collaborative efforts between countries and international organizations can enhance the sharing of expertise, resources, and data, contributing to the development of more robust early warning systems.

Early warning systems and the recognition of early warning signs are vital components in reducing the impact of earthquake hazards. While challenges exist, advancements in technology, increased global collaboration, and community preparedness efforts offer opportunities to strengthen these systems. Integrating multiple indicators, including seismic monitoring and unconventional signs, into comprehensive early warning strategies enhances our ability to respond effectively to seismic events and protect communities from the unpredictable nature of earthquakes.

E) FLOOD RESILIENCE:

Flood resilience in the context of bridge infrastructure represents a critical aspect of civil engineering and disaster preparedness. It encompasses a bridge's ability not only to withstand but also to swiftly recover from the devastating impact of flooding events. This multifaceted approach involves a comprehensive evaluation of flood risk, the implementation of proactive measures to mitigate the risk of inundation, and the strategic design of bridges capable of enduring the relentless assault of rising water levels and fast-flowing floodwaters. Flood-resilient bridge design is a synergy of engineering ingenuity, materials selection, and the integration of effective drainage systems. The ultimate goal is to ensure the sustained functionality and structural integrity of bridges, irrespective of the ferocity of the flood, while simultaneously mitigating the potential consequences that flooding may inflict upon communities and infrastructure.

a) Impact of the flooding hazard on bridges

Flooding hazards pose a significant threat to bridge infrastructure, influencing its resilience on multiple fronts. The consequences of flood events on bridges are diverse, encompassing structural damage, functional impairments, and compromised safety. The alignment and orientation of a bridge emerge as pivotal factors influencing the extent of this damage. The relationship between the bridge's positioning and the flow of floodwaters is critical; as structures aligned, perpendicular to the flood direction may face heightened vulnerability. Conversely, bridges experience less severe impact when aligned parallel or at an angle.^[9] The severity of flooding-induced damage underscores the importance of strategic planning, engineering solutions, and resilient designs to mitigate the adverse effects on bridges and ensure their longevity and safety.



Alignment and Orientation Influence:

- **Bridge Alignment:** The alignment of a bridge in relation to the flow of floodwaters can significantly influence the extent of damage. If the bridge is perpendicular to the flow, it may experience greater resistance and force from the floodwaters, potentially leading to structural damage or even collapse. Bridges aligned parallel or at an angle to the flood, direction may experience less severe impact.
- **Orientation:** The orientation of bridge components, such as piers and abutments, also plays a role. For instance, if the piers are oriented in a way that channels floodwaters directly into bridge supports, it can increase the risk of scouring and undermining the foundation, leading to structural instability.

Flood Resilience in Bridge Infrastructure:

Flood resilience in bridge infrastructure involves a multifaceted approach that incorporates a thorough evaluation of flood risk, effective engineering principles, and comprehensive disaster management strategies. The three primary components of this approach are:

Thorough Evaluation of Flood Risk:

Importance: The foundation of flood resilience is a comprehensive flood risk assessment, recognizing the potential hazards and their impact on bridges.

Flood Risk Assessment:

- **Likelihood and Magnitude of Flooding Events:** Analysing historical data, climate patterns, and relevant factors to determine the frequency of flooding events.

- **Potential Consequences:** Assessing the height, flow speed, and extent of inundation that bridges may experience during flood events.
- **Identifying Vulnerabilities:** Recognizing weaknesses in bridge design, location, or materials through the assessment.

Formulating Mitigation Strategies:

Importance: Mitigation strategies developed based on the findings of the flood risk assessment to enhance bridge resilience.

Mitigation Strategies:

- **Raising Bridge Components:** Elevating bridge components to levels safe from inundation.
- **Reinforcing Materials:** Strengthening materials to withstand prolonged exposure to water.
- **Enhancing Drainage Systems:** Improving drainage systems to prevent erosion and minimize the impact of floodwaters on bridge foundations.

Effective Disaster Management:

Importance: Integrating flood resilience into disaster management plans ensures a coordinated and swift response to mitigate the impact of flooding on bridges.

Disaster Management:

- **Coordination:** Establishing strong coordination among engineering authorities, disaster management agencies, and local communities.
- **Early Warning Systems:** Implementing advanced early warning systems to facilitate timely evacuation and response.
- **Community Preparedness:** Educating and engaging communities in flood preparedness to enhance overall resilience.

The impact of flooding on bridges influenced by the alignment and orientation of the structure. The multifaceted approach to flood resilience involves a thorough evaluation of flood risk, formulation of mitigation strategies based on assessments, and effective disaster management practices. This comprehensive approach aims to minimize the vulnerability of bridges to flooding hazards and enhance their ability to withstand and recover from such events.

b) Bridge design to counter the flooding hazard.

Flood-resistant bridge design and construction are fundamental aspects of flood resilience, ensuring that bridges can withstand and recover from the devastating impact of flooding events. This includes three key elements:

Elevation ^[10]:

Elevating bridge components above expected flood levels is a foundational and crucial aspect of flood-resistant bridge design. This engineering feat provides a robust Defence against inundation and the damaging waterborne effects that flooding can bring.

Elevation is the practice of designing and constructing bridge components, such as piers, abutments, and decks, at a height that exceeds the anticipated flood levels in a given area. This design consideration is essential because it ensures that the critical structural elements of the bridge remain above the water level during flood events.

Key points regarding elevation in flood-resistant bridge design:

- **Flood Level Prediction:**

Accurate prediction of flood levels is essential to determine the appropriate height to which bridge components should be elevated. Engineers use historical flood data, hydrological models, and floodplain mapping to estimate these levels.

- **Safety and Functionality:**

The primary goal of elevating bridge components is to ensure the safety and functionality of the bridge during and after a flood. Elevated components prevent the bridge from being submerged, allowing it to remain operational and minimizing the risk of structural damage.

- **Adaptability:**

Flood-resistant bridge designs are often adaptable to different flood scenarios. For instance, bridge can still function when floodwaters recede when adjustable or removable sections can be raised or taken off during a flood, ensuring that the.

- **Compliance with Regulations:**

Bridge designers must adhere to local building codes and regulations that specify minimum elevation requirements for structures in flood-prone areas. These regulations are in place to ensure the safety of bridges and the communities they serve.

Drainage:

Effective drainage systems are vital components of flood-resilient bridge design. These engineered systems efficiently remove water from the bridge's deck during and after a flood, preventing erosion, maintaining structural stability, and guarding against structural compromise. Key points regarding drainage in flood-resistant bridge design:

- **Drainage Systems:** Flood-resistant bridges incorporate a network of drainage] systems, including gutters, downspouts, scuppers, and drainage channels. These strategically designed systems collect and channel rainwater and floodwater away from the bridge's deck.

- **Erosion Prevention:** Efficient drainage is critical in preventing erosion of the bridge's foundations and abutments. Without proper drainage, floodwaters can erode the soil around bridge supports, compromising their stability and structural integrity.

- **Maintenance and Clearing:** Regular maintenance and clearing of drainage systems are essential to ensure their functionality. Debris, sediment, and vegetation can accumulate in drainage channels, hindering the flow of water.

Routine inspection and cleaning are necessary to keep the drainage systems in optimal working condition.

Materials:

The choice of materials is pivotal in flood-resistant bridge design. Flood-resistant materials selected the ability to withstand the corrosive effects of water and maintain structural integrity even after prolonged exposure to floodwaters. The importance of flood-resistant materials is:

- **Material Selection:** Bridge designers and engineers carefully select materials that offer resistance to the corrosive effects of water and other environmental factors. This includes choosing materials that do not deteriorate or weaken when exposed to water for extended periods.
- **Corrosion Resistance:** Many flood-resistant materials are corrosion-resistant, meaning they can withstand the corrosive action of water without significant degradation. Common materials include stainless steel, concrete, and certain types of treated wood.
- **Longevity and Durability:** Flood-resistant materials offer longevity and durability, even in flood-prone areas. These materials expected to maintain their structural integrity over the long term, reducing the need for frequent repairs or replacements.
- **Environmental Impact:** Material selection also takes into account the environmental impact. Sustainable and environmentally friendly materials may be preferred to minimize the ecological footprint of bridge construction and maintenance.

Flood-resistant bridge design and construction are multifaceted processes that involve elevating bridge components above anticipated flood levels, implementing effective drainage systems, and selecting flood-resistant materials. These measures are critical to ensure the safety, functionality, and durability of bridges during and after flooding events, ultimately minimizing the potential consequences for communities and infrastructure.

c) Retrofitting and strengthening technologies for countering the impact of flooding hazard

Retrofitting and strengthening technologies play a pivotal role in fortifying infrastructure against the impact of flooding hazards. As climate change intensifies the frequency and severity of floods, ensuring the resilience of critical structures such as bridges becomes paramount. Retrofitting involves the modification or enhancement of existing structures to improve their capacity to withstand flood-induced stresses. Strengthening technologies encompass a spectrum of engineering measures aimed at reinforcing key elements of bridges, from foundations to superstructures. This multifaceted approach involves deploying innovative materials, advanced construction techniques, and strategic design modifications. By addressing vulnerabilities identified through thorough risk assessments, these technologies not only enhance the structural robustness of bridges but also contribute to the overall resilience of communities by safeguarding vital transportation links during and after flooding events.

The following are key retrofitting and strengthening technologies employed for this purpose:

- **Elevation of Critical Components** ^[10]: Elevating critical components of a structure, such as the bridge deck, electrical systems, and utilities, above potential flood levels.

Benefits: Reduces the risk of inundation and minimizes damage to vital infrastructure components, allowing the structure to remain functional during and after a flood event.

- **Flood Barriers and Levees:** Constructing flood barriers and levees around vulnerable areas to prevent floodwaters from reaching critical infrastructure.

Benefits: Provides a physical barrier against rising water levels, offering protection to bridges and other infrastructure components. Levees are particularly effective in preventing riverine and coastal flooding.

- **Reinforcement of Structural Components:** Strengthening the structural elements of a bridge, such as beams, columns, and foundations, to withstand the impact of floodwaters.

Benefits: Improves the overall load-bearing capacity of the structure, reducing the risk of structural failure due to the dynamic forces exerted by floodwaters.

- **Use of Water-Resistant Materials:** Incorporating water-resistant or water-repellent materials in the construction or retrofitting of bridges to mitigate the effects of prolonged exposure to water.

Benefits: Enhances the durability of the structure by minimizing the absorption of water, preventing material degradation, and reducing the long-term impact of flooding.

- **Resilient Bridge Design:** Implementing design features that allow bridges to flex and adapt to the forces exerted by floodwaters, such as flexible joints and materials.

Benefits: Enhances the overall resilience of the bridge by allowing it to accommodate dynamic forces, reducing the risk of damage or failure during flooding events.

- **Scour Protection Measures:** Installing scour protection measures around bridge foundations to prevent erosion of soil and sediment during floods.

Benefits: Mitigates the risk of foundation undermining, which is a common cause of bridge failure during flooding, by reinforcing the bridge's substructure.

- **Smart Infrastructure Technologies:** Integrating smart technologies, such as sensors and monitoring systems, to provide real-time data on flood conditions and the structural health of bridges. ^[12]

Benefits: Enables proactive decision-making by providing early warnings and facilitating timely responses. Continuous monitoring helps in assessing the impact of flooding on infrastructure and aids in post-flood inspections.

- **Modular and Prefabricated Components:** Using modular and prefabricated components in bridge construction or retrofitting, allowing for quicker assembly and disassembly in the event of flood damage.

Benefits: Replacing damaged components reduces downtime and facilitates faster recovery more efficiently.

- **Vegetative and Natural Solutions:** Incorporating natural solutions, such as planting vegetation and restoring natural buffers, to absorb and slow floodwaters.

Benefits: Enhances the natural resilience of the environment surrounding bridges, reducing the force and speed of floodwaters and minimizing potential damage.

- **Improved Drainage Systems:** Upgrading drainage systems to ensure efficient water evacuation, preventing water accumulation and reducing the risk of flooding. ^[11,12]

Benefits: Enhances the bridge's ability to withstand flooding by minimizing the duration and depth of water exposure.

Retrofitting and strengthening technologies for countering the impact of flooding hazards involve a combination of elevation strategies, physical barriers, and structural reinforcements, water-resistant materials, resilient design features, scour protection, smart technologies, modular components, natural solutions, and improved drainage systems. These measures collectively contribute to the development of flood-resilient infrastructure, ensuring the longevity and functionality of bridges in the face of flooding events.

d) **Case Studies with lessons learned.**

The examination of historic floods and real-world case studies offers valuable insights and knowledge that contribute to enhancing flood resilience in bridge infrastructure. These lessons are instrumental in shaping strategies for flood risk assessment, management, and the design of flood-resistant bridges. The experiences gained from such events serve as a foundation for improving floodplain management practices and ensuring the vigilant stewardship of infrastructure.

Case Study 1: Great Mississippi Flood of 1927 ^[13]

The Great Mississippi Flood of 1927 serves as a powerful case study that provides essential lessons in proactive floodplain management, flood forecasting, and control measures. This catastrophic event underscored the importance of managing floodplains to reduce the risk of flooding.

Lesson: The key lesson from the Great Mississippi Flood of 1927 is the critical role of proactive floodplain management in achieving flood resilience. This catastrophic event served as a watershed moment in recognizing that managing floodplains is a fundamental component of flood risk reduction. It highlighted the need for comprehensive floodplain management practices, including land use planning, construction restrictions, and the fortification of flood-prone areas.



Impact: During the Great Mississippi Flood of 1927, numerous bridges along the Mississippi River suffered inundation and damage. This event brought to the forefront the urgency of enhancing flood-resistant bridge design and fortifying critical infrastructure against the ravages of floods. The lessons from this historic flood continue to shape flood risk management and resilience strategies to this day, emphasizing the need for proactive floodplain management to mitigate the impact of such catastrophic events.

Case Study 2: Hurricane Katrina (2005) ^[14]

Hurricane Katrina, which struck in 2005, serves as another significant case study that highlights the importance of designing bridges capable of withstanding extreme weather events, particularly in hurricane-prone regions. This event emphasized the necessity of elevated bridge designs and the imperative of resilience in bridge design.

Lesson: The key lesson from Hurricane Katrina is the paramount importance of designing bridges that surpass ordinary standards, especially in regions prone to hurricanes and extreme weather events. It underscored the need for bridge designs that are not just resilient but capable of withstanding the monstrous forces of extreme weather events. Elevated bridge designs became a quintessential feature to ensure that bridges remain functional even in the face of devastating storms.

- **Impact:** Hurricane Katrina inflicted severe damage on the I-10 bridges in New Orleans, primarily due to the relentless storm surge. The event demonstrated the unassailable need for resilience in bridge design. As a result, it inspired a new era in bridge design that is capable of defiantly confronting the extreme challenges posed by inclement weather. The lessons learned from this case study have significantly influenced the design and construction of bridges in hurricane-prone areas. It has prompted advancements in flood resilience strategies, encouraging engineers and authorities to adopt innovative approaches to ensure the safety and continuity of critical transportation infrastructure during extreme weather events.



These historic flood events and case studies offer valuable insights and lessons that shape strategies to enhance flood resilience in bridge infrastructure. These lessons underscore the importance of proactive floodplain management, elevated bridge designs, and the need for resilient infrastructure in regions prone to extreme weather events. By learning from these experiences, engineers, disaster management authorities, and policymakers can continue to evolve their approaches, ultimately ensuring the safety and functionality of bridges and critical infrastructure during flooding events and extreme weather conditions.

e) Early warning system and early warning signs for the hazard

UNDRR initiated and focused on the need for a Multi-Hazard Early Warning System. The focus recognized that Climate emergency affects the communities economically, and socially, and influences the environment. An integrated solution to address all natural hazards is the Multi-Hazard Early Warning System (MH-EWS). Such a system provides a comprehensive Disaster Risk Reduction strategy. UNDRR initiated a program "Words into Action" aimed to protect the most exposed communities from disasters. The focus is on four key elements of EWS. The key elements are knowledge of disaster risk based on data, analysing and forecasting of hazards and the consequences, and dissemination of information in a timely manner and accurately, to ensure the preparedness of the last person to respond to the warning.

In the realm of proactive flood risk management, advanced early warning systems stand as indispensable guardians, leveraging state-of-the-art technology vigilantly, to monitor dynamic variables such as weather patterns and river levels. These systems play a multifaceted role, providing critical information that is both timely and accurate about imminent flooding events. By employing sophisticated sensors and forecasting technologies, they enable the prediction of flood occurrences, their likely locations, anticipated magnitudes, and potential impacts on bridges and surrounding areas. The foresight offered by these systems empowers bridge managers and local authorities to take pre-emptive measures, including public notifications, coordinated evacuations, and the strategic deployment of emergency response teams. Furthermore, early warning systems facilitate the

implementation of automatic or manual strategies to mitigate flood risks, such as raising specific bridge components or activating flood barriers. Their significance lies in their ability to enhance the overall resilience of bridges, ensuring a proactive response to imminent flooding threats and minimizing potential damage through well-coordinated preparedness and mitigation efforts.

- **Timely Information:**

Early warning systems furnish timely and accurate information about impending flooding events. This includes forecasts detailing when and where floods are likely to occur, the expected magnitude, and potential impacts on bridges and surrounding areas.

- **Preparation:**

Armed with this information, bridge managers and local authorities can take proactive measures to prepare for the impending flood. This involves notifying the public, coordinating evacuations, and deploying emergency response teams to safeguard lives and infrastructure.

- **Mitigation:**

Early warning systems enable the implementation of automatic or manual measures to mitigate flood risks. For bridges, this might involve raising specific components to anticipated flood levels or activating flood barriers. These actions significantly enhance a bridge's resilience by preventing or minimizing damage.

- **Floodplain Management:**

Floodplain management is a comprehensive approach to reducing the risk of flooding for bridges and surrounding areas. Key components include prudent land use planning, restrictions on construction, and fortification of floodplains with barriers, levees, and embankments.

Early Warning Signs for Flooding Hazard:

Early warning signs for flooding hazards are critical indicators that help anticipate and prepare for potential inundation events. Monitoring rising water levels is a primary sign, detected through sensors and river gauges, providing real-time data on changing river conditions. Advanced weather forecasting technologies contribute by predicting atmospheric patterns, offering insights into the likelihood of heavy rainfall and increased flood risks. Analysing historical flood data aids in understanding recurrent patterns and potential flood-prone periods. Continuous River monitoring further enhances early detection, enabling authorities to respond swiftly. These signs collectively form a comprehensive early warning system, crucial for proactive flood risk management. By identifying changes in river conditions and anticipating precipitation patterns, these signs play a pivotal role in minimizing the impact of flooding on infrastructure and communities.

- **Rising Water Levels:** Monitoring sensors and river gauges detect rising water levels, a crucial early sign of potential flooding.

- **Weather Forecasting:** Advanced forecasting technologies predict weather patterns that may lead to heavy rainfall and increased flood risks.

- **Historical Flood Data:** Analysing historical flood data helps anticipate recurrent patterns and potential flood-prone periods.
- **River Monitoring:** Continuous monitoring of river conditions identifies changes that may indicate an elevated risk of flooding.

Hazard Mitigation Strategies:

Hazard mitigation strategies are proactive measures designed to minimize the impact of flooding events on bridges and surrounding areas. These strategies involve the integration of advanced technologies, such as early warning systems, to trigger automatic responses at the onset of flood threshold, like the elevation of critical bridge components. Additionally, the seamless integration of these systems with bridge infrastructure ensures swift adaptation to changing flood conditions. Specific mitigation measures include raising vulnerable bridge elements to predetermined levels above anticipated floodwater heights, safeguarding critical components and reducing the risk of structural damage. The overarching goal is to protect lives and property by providing advanced notice of flooding events, enabling timely evacuations, maintaining operational transportation infrastructure, and minimizing the overall impact of flooding on critical infrastructure.

Automatic Response Mechanisms:

Early warning systems can trigger automatic responses on bridges, such as the elevation of critical components, when flood reach thresholds. This minimizes reliance on manual intervention.

Integration with Infrastructure:

Integration of early warning systems with bridge infrastructure ensures a seamless response. Automated measures, like raising bridge components, contribute to swift adaptation to changing flood conditions.

Raising Bridge Components:

A specific flood-resistant measure involves elevating critical bridge elements to predetermined levels above anticipated floodwater heights. This proactive step ensures the functionality of the bridge during floods and reduces structural damage.

Safeguarding Lives and Property:

Early warning systems play a vital role in safeguarding lives and property by providing advanced notice of flooding events. This allows for timely evacuations, operational transportation infrastructure, and minimizing property damage. Advanced early warning systems deliver timely information and allow proactive preparation and mitigation strategies to counter flooding hazards. These systems, integrated with floodplain management practices, contribute to comprehensive flood resilience for bridges, ensuring the safety and functionality of critical infrastructure during and after flooding events.

F) CYCLONE RESILIENCE:

The importance of cyclone resilient bridges emphasizes the need for structures to withstand and recover from the destructive forces of cyclonic events. Highly

destructive natural phenomena, which predominantly include cyclones, hurricanes, and typhoons affect coastal infrastructure, including bridges. The resilience of bridges in the face of cyclones involves various considerations.

One crucial aspect is the design of bridges to endure the harsh conditions associated with cyclones, including high winds, heavy rainfall, and storm surges. These design elements aim to ensure the structural integrity of the bridges during the extreme weather conditions caused by cyclones. Additionally, flood prevention measures play a vital role in cyclone resilience, addressing the potential inundation of bridge areas due to heavy rainfall or storm surges.

Furthermore, it emphasizes the importance of utilizing materials that can withstand the corrosive effects of saltwater in coastal regions. This is a critical factor in ensuring the long-term durability of bridges exposed to saltwater, which is often associated with cyclonic events. The use of corrosion-resistant materials contributes to the overall resilience of bridges against the environmental challenges posed by cyclones.

Typical images of the hazard and the damage it can cause, as the few herein below, further enhance the clear illustration of the destructive impact of cyclones on bridges, highlighting the importance of resilience measures.

Visuals describe the multifaceted nature of cyclone resilience for bridges. The importance is emphasised to encompass design considerations, flood prevention measures, and the use of corrosion-resistant materials. It also highlights the essential role of cyclone resilience in ensuring public safety and maintaining the functionality of transportation networks in cyclone-prone areas. The internet has many such vivid images and video clips of the destruction and damage that past cyclones have brought about in their zone of influence.



a) Impact of cyclone hazard on bridges

The impact of cyclone hazards on bridges can be severe and multifaceted, with the potential for extensive damage depending on various factors. The alignment and orientation of the bridge play a crucial role in determining the severity of the damage caused by cyclonic events. In a cyclone-prone region, the alignment of a bridge concerning the path of the cyclone's strongest wind direction is a significant factor. If the bridge is perpendicular to the direction of the prevailing winds, it may experience increased wind forces on its broadside, leading to a higher risk of structural damage. The windward side of the bridge is particularly vulnerable, as the cyclonic winds exert intense lateral forces that can compromise the stability and integrity of the structure.

The orientation of the bridge concerning the storm surge is another critical consideration. Cyclones often bring about storm surges, causing an increase in water levels in coastal areas. If the bridge is parallel to the path of the storm surge, it may face a greater risk of inundation and hydrodynamic forces. Such forces can lead to erosion of support structures, scour around bridge foundations, and overall degradation of the bridge's substructure.

One important aspect is the elevation and topography of the bridge's location. Both these aspects contribute to the impact of cyclone hazards on the bridge. Bridges situated in low-lying areas are more susceptible to flooding and storm surges, heightening the risk of structural damage. The alignment and orientation of the bridge relative to the surrounding landscape influence the extent of exposure to these destructive elements.

All the above aspects [alignment and orientation of the structure in relation to the path of strong winds and storm surges] influence the impact of cyclone hazards on bridges. Bridges that are perpendicular or parallel to these elements face distinct risks, with potential consequences ranging from wind-induced structural damage to inundation and scour. Understanding and incorporating these factors into the design and planning of bridges in cyclone-prone areas are crucial for enhancing resilience and minimizing the potential damage caused by these natural phenomena.

Key Points of the impact of cyclone hazards on bridges:

- **Alignment and Orientation:** Bridges aligned perpendicular to the cyclone's path face higher risks due to increased exposure to strong winds and storm surges.
- **Aerodynamic Design is Crucial:** Bridges with poor aerodynamic design are at greater risk, as they may experience heightened wind resistance, contributing to potential structural damage.
- **Comprehensive Planning is Essential:** Cyclone resilience planning should consider not only the structural integrity of bridges but also their alignment and aerodynamic features to mitigate potential damage effectively.

b) Bridge design to counter the cyclone hazard.

Cyclone-resistant bridge design and construction form a crucial aspect of ensuring the resilience of bridges in cyclone-prone areas. To counter the impact of cyclones,

designers incorporate specific elements into the bridge structure to enhance its ability to withstand the destructive forces associated with these storms. In addressing the hazard of cyclones, the focus shifts to engineering practices and building strategies that fortify bridges against cyclonic forces.^[15] Cyclone-resistant bridge design involves meticulous planning and implementation to mitigate potential damages. Several key considerations play a vital role in achieving this resilience:

Wind-Resistant Design: Design of the bridges with specific features that minimize wind-induced forces to withstand the high winds associated with cyclones. This includes the utilization of aerodynamic shapes, materials, and structural elements to reduce wind resistance. Key aspects of the wind-resistant design include:

- **Streamlined Shapes:** Incorporating aerodynamic shapes in the bridge design minimizes wind resistance and turbulence, thus reducing lateral forces acting on the structure.
- **Reinforced Structures:** The use of robust materials and structures ensures the bridge's integrity during high winds, enhancing its durability in adverse weather conditions.
- **Flexible Joints:** Some bridge designs incorporate flexible joints to allow the structure to move and adapt to wind forces without compromising safety.

Storm Surge Protection:

Storm surges, often accompanying cyclones, can result in catastrophic flooding in coastal areas. Cyclone-resistant bridge design includes specific measures, as stated below, to safeguard against these surges:

- **Elevated Bridge Decks:** Designing bridges with elevated decks ensures they remain above potential floodwaters caused by storm surges, maintaining connectivity even during extreme flooding events.
- **Flood Walls:** In areas prone to severe storm surges, the design of the bridges includes integrated floodwalls and barriers to provide additional protection and prevent water inundation.
- **Reinforced Foundations:** Construction of bridges with foundations capable of withstanding the force of storm surges and wave action ensures bridge stability in challenging conditions.

Materials:

The selection of materials is critical to the long-term resilience of bridges in cyclone-prone regions. The materials used must be corrosion-resistant, durable, and capable of withstanding the corrosive effects of saltwater. Key material considerations include:

- **Corrosion-Resistant Coatings:** Applying coatings that resist corrosion is essential to prevent the degradation of structural elements over time.

- **High-Strength Materials:** Using high-strength materials, such as reinforced concrete or advanced composites, enhances the bridge's ability to withstand cyclonic forces.
- **Maintenance and Inspection:** Regular maintenance and inspection of bridges are necessary to identify and address corrosion and damage caused by exposure to saltwater and other environmental factors, ensuring the ongoing resilience of the structure.

c) Retrofitting and strengthening technologies for countering the impact of hazard

Retrofitting and strengthening technologies play a crucial role in mitigating the impact of cyclone hazards on structures, especially bridges. These technologies involve modifying existing structures to enhance their resilience and ability to withstand cyclonic forces. ^[16] The goal is not only to minimize damage during the cyclone but also to facilitate faster recovery post-occurrence.

Retrofitting Techniques:

Reinforcement of Structural Components:

This involves adding additional materials or structural elements to existing components, such as beams and columns, to enhance their load-carrying capacity.

Benefits: Increased strength and load-bearing capacity, reducing the risk of structural failure during cyclonic events.

Damping Systems:

Installation of damping systems, such as tuned mass dampers or base isolators, to absorb and dissipate energy, reducing the impact of vibrations caused by high winds or seismic activity.

Benefits: Improved structural stability and reduced dynamic response to external forces, minimizing the risk of damage.

Strengthening Foundations:

Upgrading foundation systems results in better resistance to storm surges and wave action, ensuring the overall stability of the structure.

Benefits: Increased resistance to soil erosion and foundation displacement during cyclones, preventing structural failure.

Corrosion Protection Measures:

Implementation of corrosion-resistant coatings, sacrificial anodes, or cathodic protection systems to protect structural elements from the corrosive effects of saltwater.

Benefits: Prolong the lifespan of the structure by preventing corrosion-related deterioration, ensuring long-term resilience.

Upgrading Wind-Resistant Features:

Modifying the design to incorporate enhanced wind-resistant features, such as streamlined shapes, to reduce wind-induced forces on the structure.

Benefits: Improved aerodynamics and reduced lateral forces, minimizing the risk of structural damage during cyclonic events.

Typical Scenarios and Impact:

a. Before Cyclone Event:

Scenario: The proactive protective retrofitting measures implemented, ensure the structure is prepared to face cyclonic forces.

Impact: Increased structural integrity, reduced vulnerability, and a higher likelihood of withstanding the cyclone's impact.

b. During Cyclone Event:

Scenario: Storm surges, high winds, and other cyclonic forces act on the Bridge.

Impact: The retrofitting measures help in reducing structural damage, preventing failure, and maintain functionality to a certain extent.

c. Post-Cyclone Event:

Scenario: The cyclone has passed, and the region is in the recovery phase.

Impact: Despite potential damage, the retrofitting measures contribute to easier assessment and quicker recovery. The structure's enhanced resilience facilitates faster restoration of transportation links.

Recovery Strategies:

a. Damage Assessment:

A thorough inspection to identify and assess the extent of structural damage.

Strategy: Employ skilled engineers and inspection teams to conduct detailed assessments, prioritizing safety-critical elements.

b. Immediate Repairs:

Conducting immediate repairs to address critical damage and ensure the structure's safety.

Strategy: Mobilize repair teams equipped with the necessary materials and tools to address urgent issues promptly.

c. Community Engagement:

Engaging with affected communities to understand their needs and concerns.

Strategy: Collaborate with local authorities and communities to plan and execute recovery efforts that prioritize essential infrastructure and services.

d. Continual Monitoring and Maintenance:

Implementing ongoing monitoring systems to track any post-cyclone structural changes and scheduling regular maintenance.

Strategy: Invest in monitoring technologies and establish a maintenance schedule to address any latent issues and ensure long-term resilience.

e. Future Retrofitting:

Considering additional retrofitting measures based on lessons learned from the cyclone event.

Strategy: Continuously evaluate and update retrofitting strategies to adapt to evolving climate conditions and potential changes in hazard patterns.

d) Case studies with lessons learned:

Hurricane Katrina (2005) - New Orleans, USA ^[14]

Hurricane Katrina, one of the most devastating hurricanes in U.S. history, caused severe flooding and destruction in New Orleans. Levee failures led to widespread inundation, affecting critical infrastructure, including bridges, roads, and public facilities.

- **Critical Infrastructure Vulnerability:** The vulnerability of critical infrastructure, including levees, highlighted the need for robust engineering and better disaster preparedness.
- **Importance of Evacuation Plans:** The inadequacy of evacuation plans underscored the importance of well-organized and communicated evacuation strategies for vulnerable communities.

Mitigation Measures Initiated Post-Occurrence:

Enhanced Levee Systems:

- **Action:** Substantial investments made in reinforcing and upgrading the levee systems to withstand stronger storm surges.

Lesson Learnt: Adequate investment in resilient infrastructure is crucial for safeguarding against future cyclonic events.

Improved Evacuation Protocols:

- **Action:** Revisions and improvements made to evacuation plans, including better communication and transportation strategies.

Lesson Learnt: A comprehensive and well-executed evacuation plan is vital to protect lives and reduce the impact on communities.

Cyclone Phailin (2013) - Odisha, India

Cyclone Phailin, one of the strongest cyclones to hit the Indian subcontinent, in the Indian state of Odisha. While it caused significant damage, effective evacuation efforts minimized casualties.

- **Early Warning Systems:** Early warning systems and community preparedness initiatives resulted in the success of evacuation and safety of humanity.
- **Community Engagement:** Communities that actively participated in preparedness programs exhibited greater resilience and ability to cope with the cyclone.

Mitigation Measures Initiated Post-Occurrence:

Strengthening Early Warning Systems:

- **Action:** Investments made to enhance early warning systems, including improved meteorological forecasting and communication channels.

Lesson Learnt: Timely and accurate information is critical for enabling communities to prepare and respond effectively.

Community-Based Disaster Preparedness:

- **Action:** Emphasis on community engagement and education, empowering local residents with knowledge about cyclone preparedness.

Lesson Learnt: Engaging communities in disaster preparedness programs increases their resilience and ability to cope with the impact of cyclones.

Typhoon Haiyan (2013) - Philippines

Typhoon Haiyan, one of the strongest tropical cyclones on record, struck the Philippines, causing widespread devastation. The storm surge and strong winds led to significant loss of life and infrastructure damage.

- **Vulnerability of Coastal Areas:** The vulnerability of coastal areas to storm surges highlighted the need for improved infrastructure in these regions.
- **Emergency Response Challenges:** The challenges faced in delivering prompt and effective emergency response underscored the importance of well-coordinated disaster relief efforts.

Mitigation Measures Initiated Post-Occurrence

Coastal Infrastructure Resilience:

- **Action:** Initiatives launched to improve the resilience of coastal infrastructure, including the construction of storm surge barriers and elevated structures.

Lesson Learnt: Coastal regions require specialized infrastructure to mitigate the impact of storm surges.

Enhanced Disaster Response Planning:

- **Action:** Emergency response plans reviewed and enhanced, focusing on coordination, resource allocation, and timely assistance to affected areas.

Lesson Learnt: Effective disaster response requires meticulous planning and coordination among various agencies and organizations.

These case studies highlight the varied impacts of cyclones and the importance of tailored mitigation strategies. Lessons learned emphasize the significance of robust infrastructure, early warning systems, community engagement, and well-coordinated emergency response efforts in reducing the impact of cyclone hazards.

e) Early warning system and early warning signs for the cyclone hazard

UNDRR has initiated a program that will ensure that the entire world remain protected by 2027 using the "Early Warning for All". This global initiative to ensure

that everyone on Earth remains protected by early warnings by 2027 is being fast-tracked into action on the ground. A record-breaking tropical cyclone in Southeast Africa shows the paramount importance of these services to ensure that lives and livelihoods remain protected from increasingly extreme weather and climate events. Over 100 countries the world over have adapted the system and few gaps remain in America and Africa. Countries that have adapted the system have an operational warning and alerting services. These systems incorporate hazard, exposure and vulnerability information. Advanced tropical modelling is used to predict and track the changes in intensity of the cyclone. This is possible due to data sharing, modelling and expertise gained due to past events. Use of technology like drones and mass dissemination to the entire population using smart phones enhances the available knowledge about risk. Improvement in dissemination of warning communication by mobile and internet connectivity is an example of use of technology.

Meteorological Data:

Accurate and timely meteorological data is the foundation of an effective early warning system. This data tracks the development and path of cyclones, enabling the prediction of their trajectories and assessing potential impacts on bridges.

Importance: Timely and precise meteorological information allows bridge managers and local authorities to make informed decisions regarding evacuation, infrastructure preparedness, and risk mitigation.

Evacuation Planning:

Early warning systems play a crucial role in facilitating the timely evacuation of residents in high-risk areas. They also allow bridge users to find alternative routes in advance of a cyclone's arrival.

Importance: Proper evacuation planning helps ensure the safety of communities and minimizes the risk of congestion on bridges during cyclonic events, reducing the likelihood of accidents or delays.

Risk Communication: ^[17]

Effective risk communication is essential for informing the public, bridge operators, and local authorities about an impending cyclone. This includes conveying information about potential consequences and recommending safety measures.

Importance: Clear and timely communication enhances public awareness and preparedness. It ensures that individuals and organizations can take appropriate actions to safeguard lives and property.

Emergency Response Plans:

Early warning systems contribute to the development and implementation of emergency response plans. Coordination with local authorities, emergency services, and disaster management agencies is a key aspect of this planning.

Importance: Collaborative emergency response planning ensures a swift and organized reaction to cyclone-related emergencies. It includes protocols for evacuation, rescue operations, and recovery efforts, optimizing the overall response to the hazard.

Coordination with Local Authorities:

Bridge management agencies establish strong coordination with local authorities, emergency services, and disaster management agencies. This collaboration ensures a unified and efficient response to cyclone-related emergencies.

Importance: Coordinated efforts streamline evacuation processes, resource allocation, and recovery operations. It maximizes the effectiveness of response measures and minimizes the potential impact of the cyclone on bridges and surrounding infrastructure.

Communication Systems: ^[17]

Reliable communication systems are crucial for coordinating emergency responses and disseminating information to the public. These systems must be resilient to cyclone-related disruptions, ensuring continuous and effective communication.

Importance: Uninterrupted communication is vital for issuing timely warnings, providing updates, and coordinating emergency efforts. Resilient communication systems enhance the overall effectiveness of early warning systems.

Early Warning Signs for Cyclone Hazards:

- **Sea Level Rise:** A rapid rise in sea level, especially in coastal areas, can indicate the onset of a cyclone.
- **Changes in Atmospheric Pressure:** A significant drop in atmospheric pressure is often an early indicator of an approaching cyclone.
- **Wind Patterns:** Sudden changes in wind patterns, including gusty winds and shifts in direction, can signal the proximity of a cyclonic system.
- **Cloud Formation:** Distinctive cloud formations, such as the development of an eye or an increase in cloud cover, may indicate cyclone formation.

Cyclone Hazard Mitigation: ^[17]

- **Preparedness and Training:** Regular drills and training exercises help communities and response teams prepare for cyclone events.
- **Infrastructure Resilience:** Designing and retrofitting bridges to withstand cyclonic forces, including storm surges and high winds.
- **Vegetative Cover:** Preserving or restoring natural vegetative cover, such as mangroves, can act as a natural barrier against storm surges.
- **Community Engagement:** Educating and involving communities in cyclone preparedness and mitigation efforts increases resilience and ensures a more informed response.

Early warning systems encompass meteorological data, evacuation planning, risk communication, emergency response plans, coordination with local authorities, and reliable communication systems. Early warning signs for cyclones include sea level rise, atmospheric pressure changes, wind patterns, and distinctive cloud formations. Cyclone hazard mitigation involves a combination of preparedness, infrastructure resilience, vegetative cover, and community engagement.

Integration of a comprehensive cyclone risk-management strategy influenced the effectiveness of these measures.

G) LANDSLIDE RESILIENCE:

Landslide resilience stands as a crucial focus within civil engineering, specifically tailored to fortify the structural integrity and safety of bridges in regions susceptible to landslides. This meticulously created comprehensive approach to design and construct bridges that can endure the formidable challenges posed by landslides, characterized by the abrupt movement of soil or rock down slopes. The resilience framework encompasses pivotal elements, notably landslide risk assessment, landslide-resistant bridge design and construction, and drawing valuable insights from historical landslides and case studies.

Landslides, often triggered by factors such as heavy rainfall, earthquakes, or human activities, pose a significant threat to infrastructure. The main characteristic of landslides is the sudden and often unpredictable displacement of soil or rock masses along slopes, potentially endangering bridges and their surrounding areas. The inherent unpredictability and rapid nature of landslides necessitate a proactive and adaptive approach to ensure the robustness of bridge structures in landslide-prone regions. ^[18]

Heavy rainfall saturating the soil, seismic activities destabilizing slopes, or human activities altering the natural landscape trigger Landslides.

Characteristic of Landslides is the rapid movement of soil or rock masses down slopes. This can result in debris flows, rock falls, or slumps, each posing unique challenges to bridge resilience.

Landslide resilience in bridge engineering is a dynamic field addressing the complex challenges posed by landslide hazards. It combines risk assessment, robust design principles, and historical knowledge to ensure that bridges can withstand the unpredictable forces associated with landslides, thereby safeguarding both infrastructure and public safety.

a) Impact of the landslide hazard on bridges

Landslide hazards present a substantial risk to bridges, exerting powerful forces and mass movement that result in severe consequences. The impact encompasses structural damage, destabilization, and the looming potential for total collapse. This peril jeopardizes both the functionality and safety of the bridge, underscoring the need for strategic measures to mitigate the devastating effects of landslides on critical infrastructure. ^[19]

- **Structural Damage:** Landslides can cause direct impact on bridge elements, leading to structural damage. Falling debris, rocks, or soil can collide with bridge components, compromising their integrity and posing a risk of failure.
- **Compromised Stability:** The foundation of a bridge is particularly vulnerable to landslides. If the underlying soil erodes or shifts due to a landslide, it can compromise the stability of bridge supports, increasing the likelihood of structural failure.

- **Complete Collapse:** In severe cases, landslides can exert forces that exceed the structural capacity of the bridge, resulting in complete collapse. The alignment and orientation of the bridge play a critical role in determining the vulnerability to such catastrophic events.

Alignment and Orientation Influence:

Alignment and orientation are pivotal factors influencing the impact of landslide hazards on bridges. If a bridge is aligned perpendicular to the potential landslide movement, it becomes more susceptible to severe damage or collapse due to the direct force and impact of the landslide. Similarly, the orientation of bridge components, such as piers and abutments, plays a crucial role; if these elements are in the direct path of landslide movement, they are more likely to endure the most impact, escalating the overall damage. Strategic alignment of bridges parallel or at an angle to potential landslide paths is a key mitigation strategy, reducing the direct impact and minimizing the risk of catastrophic failure. This emphasizes the importance of thoughtful planning and design to enhance bridge resilience in landslide-prone areas.

- **Bridge Alignment:** The alignment of a bridge concerning the direction of potential landslides is crucial. If a bridge is aligned perpendicular to the potential landslide movement, it may experience greater impact and force, increasing the risk of structural damage or collapse.
- **Orientation:** The orientation of the bridge components, such as piers and abutments, also influences the severity of damage. If these elements are directly in the path of landslide movement, they are more likely to withstand the worst of the impact, escalating the damage.

Mitigation Strategies:

Mitigation strategies for landslide hazards involve proactive measures to minimize the impact on bridges and surrounding areas. Thorough geotechnical studies conducted assess the susceptibility of bridge sites, informing strategic design and construction. Implementing slope stabilization techniques, such as retaining walls and rock bolts, helps reduce the risk of landslides affecting the bridge's stability. Proper alignment, ensuring the bridge is parallel or angled to potential landslide paths, minimizes direct impact and lowers the risk of catastrophic failure. Additionally, reinforcing vulnerable bridge components enhances their resilience against the forces exerted during landslides, contributing to overall hazard mitigation and the safety of critical infrastructure.

- **Geotechnical Studies:** Conducting thorough geotechnical studies to assess the susceptibility of bridge sites to landslides, helping inform bridge design and construction in landslide-prone areas.
- **Slope Stabilization:** Implementing slope stabilization measures, such as retaining walls, rock bolts, or vegetation, to reduce the risk of landslides affecting the bridge.
- **Proper Alignment:** Strategic alignment of bridges parallel or at an angle to potential landslide paths can minimize the direct impact and reduce the risk of catastrophic failure.

- **Structural Reinforcement:** Reinforcing bridge components, especially those vulnerable to landslide impact, to enhance their resilience and capacity to withstand the forces exerted during a landslide.

b) **Bridge design to counter the landslide hazard.**

Incorporating Flexible Foundations:

Explanation: Designing bridges with flexible foundations is essential for withstanding the dynamic forces associated with landslides. These foundations allow the bridge structure to adapt to ground movement, minimizing the risk of structural damage during a landslide event.

Significance: Flexible foundations enhance the bridge's ability to withstand the forces exerted during landslides, reducing the likelihood of structural failure. This design element contributes significantly to the overall resilience of the bridge in landslide-prone areas.

Use of Reinforced Materials:

Explanation: Incorporating reinforced materials in bridge construction is crucial for resilience against landslides. Materials with enhanced strength and durability help the bridge withstand the impact of debris and soil movement during a landslide.

Significance: The use of reinforced materials ensures that the bridge can endure the forces exerted by landslides, minimizing the risk of damage. This resilience factor is particularly vital for bridges located in regions with a high susceptibility to landslide events.

Effective Drainage Systems:

Explanation: Integrating effective drainage systems into bridge design is essential for managing water runoff during and after landslides. Proper drainage prevents the accumulation of water that can exacerbate landslide risks and compromise bridge stability.

Significance: Well-designed drainage systems contribute to landslide resilience by minimizing the impact of water on the bridge structure. This proactive measure ensures that the bridge remains functional and safe in the aftermath of landslide events.

Landslide Barriers:

The implementation of protective measures, such as landslide barriers, is a fundamental aspect of landslide-resistant bridge design. Landslide barriers act as a crucial bulwark, strategically placed to mitigate the impact of landslides on the structure, thereby enhancing the bridge's overall resilience.

Strategic Placement: Landslide barriers strategically placed along the potential paths of landslides, acting as a physical barrier to impede and redirect the flow of soil or rock mass away from the bridge structure.

Structural Design: The design of landslide barriers involves considerations of height, strength, and flexibility to effectively absorb and dissipate the energy generated during a landslide, minimizing the impact on the bridge.

Reinforced Foundations:

Ensuring that bridge foundations are both robust and stable is of utmost importance in preventing displacement or damage during landslides. Reinforced foundations provide a sturdy base capable of withstanding the forces exerted by landslides, thereby safeguarding the structural integrity of the bridge.

Deep Foundations: In landslide-prone areas, deep foundations are often employed to anchor the bridge securely into stable soil or rock layers beneath the potentially landslide-prone surface layers.

Pile Installation: Common usage of Piles (whether driven or drilled) for landslide-resistant bridge foundations enhance load-bearing capacity and resist lateral forces induced by landslides.

Material Selection:

The judicious selection of materials with the appropriate strength and durability is a cornerstone of landslide-resistant bridge construction. Choosing the right materials is crucial for withstanding the formidable forces of landslides, thereby enhancing the bridge's capacity to endure such events.

High-Strength Materials: The use of high-strength materials, such as reinforced concrete and advanced steel alloys, in key structural components enhances the overall resilience of the bridge against landslide-induced forces.

Durability Considerations: Materials selected for landslide-resistant bridges undergo rigorous durability assessments, considering factors such as resistance to erosion, weathering, and chemical degradation to ensure long-term stability.

Landslide-resistant bridge design and construction demand a holistic approach, encompassing protective measures like landslide barriers, reinforced foundations, and the meticulous selection of materials. The strategic placement and design of landslide barriers act as a frontline defence, redirecting potential landslides away from critical bridge components. Reinforced foundations, particularly utilizing deep foundations and piles, anchor the bridge securely, preventing displacement during landslide events. Material selection, focusing on high-strength and durable materials, ensures the bridge's overall resilience against the forces exerted by landslides. This intentional integration of measures fortifies bridges, making them more capable of withstanding the challenges posed by landslides, ultimately enhancing safety and sustainability in vulnerable terrains.

c) Retrofitting and strengthening technologies for countering the impact of Landslide hazards:

Retrofitting and strengthening technologies play a vital role in mitigating the impact of landslide hazards on infrastructure, focusing particularly on bridges. These measures are designed to enhance the overall resilience of structures, fortifying them against the powerful forces exerted during landslides.^[20] Key strategies involve reinforcing bridge components vulnerable to landslide impact, implementing slope stabilization measures, and conducting geotechnical studies to inform design and construction. In typical scenarios, retrofitting ensures structural integrity, minimizes the risk of collapse, and safeguards infrastructure

in landslide-prone areas, contributing to increased safety and longevity. Key strategies and typical scenarios include:

Flexible Foundation Design:

Description: Implementing a flexible foundation design that allows the bridge to accommodate ground movement during a landslide.

Benefits: This approach minimizes the transfer of landslide forces to the bridge, reducing the risk of structural damage.

Slope Stabilization Measures:

Description: Employing slope stabilization techniques such as retaining walls, soil nails, and rock bolts to secure landslide-prone areas.

Benefits: Reinforcing slopes helps prevent soil erosion and reduces the likelihood of landslides affecting the bridge.

Debris Flow Barriers:

Description: Installing debris flow barriers or catchment systems to intercept and divert debris flow away from the bridge.

Benefits: Prevents debris accumulation around the bridge, minimizing the risk of structural damage and facilitating easier post-landslide recovery.

Rock-fall Protection Structures:

Description: Constructing rockfall protection structures, such as catch fences and attenuator barriers, to mitigate the impact of falling rocks on the bridge.

Benefits: Shields the bridge from the destructive forces of rockfalls, safeguarding structural integrity.

Monitoring and Early Warning Systems:

Description: Implement monitoring systems, including sensors and geotechnical instruments, to detect early signs of slope instability.

Benefits: Provides early warnings, enabling authorities to take preventive actions, such as closing the bridge or implementing traffic restrictions.

Typical Scenarios:

In typical landslide scenarios, bridges face the peril of structural damage and compromised stability. The forceful mass movement of debris, rocks, or soil during a landslide can collide with bridge components, risking structural integrity and potential collapse. The alignment of the bridge plays a pivotal role, with structures aligned perpendicular to the landslide movement being more susceptible to severe impact. Orientation matters too, as elements directly in the path of landslide movement are at higher risk. Mitigation involves geotechnical studies, slope stabilization, strategic alignment, and structural reinforcement to enhance bridge resilience in landslide-prone areas.

Slope Failure Impact:

Scenario: Landslide-induced slope failure approaching the bridge.

Impact: Landslide forces can result in the undermining of bridge foundations and structural damage.

Mitigation: Flexible foundation design and slope stabilization measures reduce the transfer of forces and reinforce the slope.

Debris Flow Threat:

Scenario: Debris flow originating from higher elevations threatening the bridge.

Impact: Debris accumulation around the bridge poses a risk of structural damage and blockage.

Mitigation: Debris flow barriers divert and control debris, protecting the bridge and facilitating easier clean-up post-landslide.

Rock-fall Hazard:

Scenario: Falling rocks from unstable slopes endangering the bridge.

Impact: Direct impact of rocks can compromise the bridge's structural integrity.

Mitigation: Rock-fall protection structures intercept and absorb falling rocks, minimizing the impact on the bridge.

Recovery Strategies Post-Landslide:

Recovery strategies post-landslide are pivotal to restoring functionality and safety to bridges affected by landslide hazards. Following a landslide event, immediate actions include conducting thorough damage assessments to gauge the extent of structural compromise. The clearance of debris and restoration of access routes are critical initial steps, facilitating subsequent repair and reconstruction efforts. Geotechnical investigations help identify areas prone to future landslides, informing strategic design modifications for enhanced resilience ^[21]. Implementation of slope stabilization measures and reinforcing bridge components ensure long-term stability, minimizing the risk of recurrent landslide impacts. Collaborative efforts between engineering authorities and disaster management agencies play a central role in expeditious recovery, ensuring the timely restoration of vital transportation infrastructure.

- **Rapid Assessment:**

Conducting a swift assessment to gauge the extent of damage and identify immediate safety concerns.

- **Clearance and Restoration:**

Clearing debris and restoring access to the bridge to facilitate subsequent repair and recovery efforts.

- **Structural Evaluation:**

Thoroughly evaluate the structural integrity of the bridge to identify areas requiring repair or reinforcement.

- **Reconstruction and Retrofitting:**

Implementing reconstruction and retrofitting measures based on the assessment findings to enhance the bridge's resilience against future landslide hazards.

- **Vegetative Cover Restoration:**

Replanting vegetation and restoring natural buffers to stabilize slopes and reduce the risk of future landslides.

- **Enhanced Monitoring Systems:**

Upgrading monitoring systems to enhance real-time detection of slope instability and early warning capabilities.

- **Community Education and Preparedness:**

Educating communities on landslide risks and implementing preparedness measures to ensure a coordinated response in the event of future hazards.

Retrofitting and strengthening technologies for landslide hazards involve flexible foundation design, slope stabilization, debris flow barriers, rockfall protection structures, and monitoring systems. These measures mitigate the impact of typical landslide scenarios, and post-landslide recovery strategies include rapid assessment, clearance, structural evaluation, reconstruction, and community education for future preparedness.

d) Case studies with lessons learned.

Historic landslides and in-depth case studies are invaluable resources that contribute significantly to the development of effective landslide resilience strategies. These studies involve meticulous investigations and thorough analyses of specific landslide events, offering insights into their causes, effects, and responses. Here, we delve into two case studies that exemplify the lessons learned from historic landslides.

Oso Landslide (2014):

- **Lesson:** The Oso Landslide in Washington serves as a poignant reminder of the critical importance of effective landslide risk assessment and the imperative need for slope stabilization measures in regions prone to landslides. The tragic event underscored the necessity for robust monitoring and early warning systems to mitigate the impacts of landslides.

- **Impact:** The Oso Landslide, which occurred in 2014 and buried a section of State Route 530, resulted in the loss of lives and extensive damage to bridges. The aftermath accentuated the vital significance of comprehensive slope management in mitigating landslide risks and preserving the functionality of bridges. As a response to this event, improvements made in monitoring technologies and early warning systems, aiming to enhance preparedness and responsiveness to potential landslides.

Big Sur Landslide (2017):

- **Lesson:** The landslide in Big Sur, California, emphasized the necessity for meticulous bridge design capable of withstanding landslides. It highlighted the importance of adaptive measures such as rockfall barriers and flexible support systems to enhance resilience in landslide-prone areas.

- **Impact:** The Big Sur Landslide of 2017 led to the closure of a portion of Highway 1, resulting in the isolation of communities. The lessons drawn from this event played a crucial role in shaping bridge design and maintenance practices. Engineers recognized the need for bridges to not only endure but also adapt to the dynamic forces of landslides. As a result, landslide-resistant features, including rock fall barriers and flexible support systems, incorporated into bridge construction and maintenance strategies to improve their resilience.

2005 La Conchita, California landslide

The 2005 La Conchita landslide stands as a poignant example of the destructive force of natural disasters and the challenges in mitigating their impact. On January 10, 2005, this close-knit community in California witnessed a tragic event as a massive landslide engulfed the area. Despite prior occurrences of landslides and the voiced apprehensions of residents regarding the vulnerability of the hillside, the disaster unfolded.



Local authorities had undertaken measures to enhance the stability of the hill, underscoring the complexity of predicting and preventing such incidents. The tragedy serves as a stark reminder of the delicate balance between human settlement and the unpredictable forces of nature, prompting reflections on the efficacy of preventative measures and the need for comprehensive strategies to safeguard communities in landslide-prone regions. The La Conchita landslide of 2005 continues to be a case study that informs discussions on land-use planning, disaster preparedness, and community resilience in the face of geological hazards.

2010 Zhouqu, China landslide

The 2010 Zhouqu, China landslide stands as a haunting testament to the devastating consequences of natural disasters. Striking with ferocity on August 8, 2010, the landslide, triggered by incessant heavy rainfall, unfolded as a catastrophic event in the region. The aftermath was nothing short of tragic, claiming the lives of over 1400 individuals and leaving a trail of destruction in its

wake. Bridges and roads succumbed to the force of nature, exacerbating the impact on the community.



The economic toll was staggering, emphasizing the vulnerability of the region to such hazards and underscoring the urgent need for heightened preparedness and resilience. This incident serves as a poignant reminder of the unpredictable nature of geological phenomena, urging communities and authorities to adopt a more cautious and vigilant approach in the face of potential disasters.

The lessons drawn from the Zhouqu landslide resonate globally, emphasizing the imperative for comprehensive risk mitigation strategies to safeguard against the profound consequences of natural calamities.

In short, these case studies show case that the lessons drawn from historic landslides encompass various facets, ranging from risk assessment and early warning systems to slope stabilization, bridge design, material selection, and emergency response strategies. By integrating these lessons into landslide resilience strategies, engineers and policymakers can enhance the safety of communities and infrastructure in regions prone to landslides.

e) Early warning system and early warning signs for the hazard [22]

UNDRR has published Words into Action as a guideline for the early warning system. This publication derives its success, based on expertise from across the world, community practices, and a network of disaster risk reduction organizations. The people-centric approach is the hallmark of the system suggested.

UNDRR adopted the multi-Hazard early warning system. For Landslides, various warning systems are available. Commonly referred to as Landslide Early Warning System (LEWS) has a bottom-up approach. This system relies on knowledge and participation of locals. This system addresses the important aspect of evacuation route planning and provision of emergency shelters. It fosters a participation-based approach to implement disaster risk reduction. Implemented largely in South America.

Another system adopted the method to detect movement, which is the main characteristic of landslides. Various movement-monitoring sensors like extensometers, seismometers integrated with global positioning systems (GPS), aerial photography, and satellite imagery enable warning with varying degrees of accuracy.

In Japan, the KIKIKURU warning system enables local communities to pinpoint rainfall-related landslide areas. It covers the entire country with a regularly updated coloured-grid warning pattern on a map, with very high spatial resolution. Various types of indices calculate the potential of landslides inundations and floods. Japan Meteorological offices around the country pool the information and data to enhance the accuracy of the system. The name in local language means, "Risk is Imminent". The backbone of KIKIKURU is the network of highly sensitive networks inter-connected. Whenever movement above normal happens, the sensors record the same and data shared over the network. Multiple records from a limited geographical area activates the detection analysis module of the system. Various government departments related to transport, infrastructure and tourism get this data from analysis results. Filtered data eliminates false alarms. Affected risk zones get the real and active risk alert.

Advanced early warning systems for landslide hazards are pivotal in proactive risk management, employing sophisticated technologies like sensors and satellite imagery. These systems continuously monitor changes in soil stability and ground movement, enabling the detection of potential landslides. Key elements comprise real-time data analysis, ensuring swift identification of anomalies, and robust communication networks for rapid dissemination of alerts to communities at risk. By leveraging these technologies, early warning systems play a critical role in mitigating the impact of landslides by providing timely notifications, allowing for preparedness, evacuation, and effective emergency response measures. Key elements include:

Monitoring Technologies:

Sophisticated sensors, satellite imagery, and ground-based monitoring systems employed to track changes in soil stability, ground movement, and other indicators of potential landslides.

- **Real-time Data Analysis:**

Continuous real-time analysis of data collected from monitoring systems enables the identification of anomalies and early signs of slope instability, allowing for swift response measures.

- **Communication Networks:**

Early warning systems integrated with robust communication networks to ensure rapid dissemination of alerts to residents, emergency services, and relevant authorities.

Early Warning Signs for Landslide Hazard:

Early warning signs for landslide hazards include observable changes in topography, such as sudden tilting or deformation of the ground, signalling potential instability. The appearance of new cracks or fractures on slopes or

structures may indicate underlying stress, while unusual water flow patterns, such as increased surface flow or new springs, can suggest heightened soil saturation and landslide risk. Additionally, alterations in vegetation, such as wilting, uprooting, or sudden changes in patterns, serve as indicators of subsurface movements and soil instability. Recognizing these signs is crucial for timely evacuation and mitigation efforts, contributing to effective landslide hazard management and minimizing the potential impact on communities and infrastructure.

- **Changes in Topography:**

Observable alterations in the landscape, such as sudden tilting or deformation of the ground, may indicate potential instability.

- **Cracks and Fractures:**

The appearance of new cracks or fractures on slopes or structures may signal underlying stress in the terrain, signalling an increased risk of landslides.

- **Unusual Water Flow Patterns:**

Anomalous patterns of water runoff, including increased surface flow or the emergence of new springs, can be indicative of heightened soil saturation and potential landslide risk.

- **Vegetation Changes:**

Signs such as wilting, uprooting, or sudden changes in vegetation patterns can signify subsurface movements and instability in the soil.

Landslide Hazard Mitigation:

Landslide hazard mitigation involves a multi-faceted approach to reduce the risk and impact of landslides. This includes implementing early warning systems that utilize monitoring technologies and real-time data analysis to detect signs of instability. Mitigation strategies encompass prudent land use planning, geotechnical assessments, and zoning regulations to restrict construction in high-risk areas. Additionally, measures like maintaining or restoring vegetative cover, improving drainage infrastructure, and constructing retaining structures employed stabilize slopes and prevent soil movement. Community education and awareness programs play a crucial role in informing residents about landslide risks, while emergency response training ensures communities are well-prepared to respond effectively in case of a landslide event. Overall, landslide hazard mitigation aims to enhance resilience and protect lives and infrastructure through a combination of proactive planning, structural measures, and community engagement.

- **Early Warning Response Plans:**

Establishing community-specific early warning response plans that outline evacuation routes, emergency shelters, and communication strategies to ensure swift and organized responses to landslide alerts.

- **Land Use Planning and Zoning:**

Implementing prudent land use planning and zoning regulations to restrict construction in high-risk landslide areas and prevent further development in vulnerable zones.

- **Geotechnical Assessments:**

Conducting comprehensive geotechnical assessments to identify areas prone to landslides and implementing necessary stabilization measures, such as slope reinforcement and retaining structures.

- **Vegetative Cover and Erosion Control:**

Promoting the maintenance or restoration of natural vegetation helps stabilize soil, absorb excess water, and reduce the risk of erosion that can trigger landslides.

- **Drainage Infrastructure:**

Improving drainage infrastructure to manage excess water effectively and prevent saturation of slopes, reducing the likelihood of landslides.

- **Structural Measures:**

Constructing retaining walls, embankments, and other structural measures to stabilize slopes and prevent soil movement in landslide-prone areas.

- **Community Education and Awareness:**

Conducting educational programs to increase community awareness about landslide risks, early warning signs, and the importance of preparedness and evacuation.

- **Emergency Response Training:**

Training emergency response teams and local communities in effective response strategies, including search and rescue operations, first aid, and evacuation procedures.

Early warning systems for landslide hazards involve monitoring technologies, real-time data analysis, and robust communication networks. Early signs of landslide risk include changes in topography, cracks, unusual water flow patterns, and vegetation changes. Landslide hazard mitigation strategies encompass comprehensive planning, geotechnical assessments, vegetation management, drainage improvements, structural measures, and community education, collectively aiming to reduce vulnerability and enhance resilience to landslide events.

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METHODOLOGY TO EVALUATE THE IMPACT OF NATURAL HAZARDS ON THE DETERIORATION PROCESS IN EXISTING BRIDGES

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A) Introduction

Bridges, as vital components of infrastructure, play a critical role in connecting communities and facilitating transportation. From the subtle symptoms that manifest over time to the underlying causes rooted in the forces of nature, understanding this nexus is imperative for engineers, researchers, and policymakers alike. However, the relentless exposure to natural hazards presents a formidable challenge to their longevity and structural integrity.

This comprehensive exploration delves into the intricate interplay between natural hazards, the deterioration process in existing bridges, and the subsequent impact on performance.

These symptoms often serve as early indicators of underlying structural issues. Cracks, rust, and deformation are among the visible signs that demand attention. Understanding how these symptoms manifest and evolve over time provides valuable insights into the broader challenges faced by bridges in the presence of natural hazards.

To comprehend the impact of natural hazards on the deterioration process, one must first recognize the subtle yet telling symptoms exhibited by existing bridges. This essentially requires one to recognize the failure impact of natural hazards on bridges and then comprehend how these forces affect the established deterioration process in the existing bridge.

B) Failure influence on Bridges due to forces of natural hazards:

1. Earthquakes: ^[2]

The failure impacts of bridges during earthquakes can have severe consequences, leading to various types of damage. The following types of damage along with the potential impacts are:

Reinforced Concrete (RC) Pier Failure:

- **Impact:** Failure at the cut-off or plastic hinges due to inadequate structural detailing can lead to the collapse of bridge piers.
- **Consequence:** Loss of vertical support, potential bridge collapse, and disruption of transportation routes.
- **Failure Mechanism:** Inadequate structural detailing for bending strength and ductility, leading to failure at the cut-off of longitudinal bars or plastic hinges. Insufficient shear resistance in the middle of the piers may also contribute to failure.

Steel Box-Pier Failure:

- **Impact:** Local buckling, especially at the bottom corners, may result in the total collapse of piers.
- **Consequence:** Structural failure, potential bridge collapse, and risk to public safety.
- **Failure Mechanism:** Local buckling, especially at the bottom corners of the steel box-pier, triggered by events like weld failure. Local buckling results in a loss of load-carrying capacity and may lead to total collapse.

Bearing Failure:

- **Impact:** Insufficient design capacity or connection issues may lead to bearing failure.
- **Consequence:** Loss of support, potential misalignment of structural elements, and increased vulnerability during subsequent seismic events.
- **Failure Mechanism:** Insufficient design capacity or poor connection with the deck or pier, leading to failure of the bridge bearings. This failure may occur due to the inability of the bearings to absorb seismic forces adequately.

Large Displacement of Substructure:

- **Impact:** Ground failure, liquefaction, and fault rupture can cause significant movement of substructure elements.
- **Consequence:** Structural misalignment, foundation damage, and potential collapse, affecting overall bridge stability.
- **Failure Mechanism:** Ground failure, liquefaction, and fault rupture causing significant movement of the substructure. Slope failures near abutments and foundation settlements under piers are examples of mechanisms leading to large displacements.

Deck Unseating:

- **Impact:** Rotating forces during an earthquake may cause deck unseating, particularly in curved or skew bridges.
- **Consequence:** Disconnection of the deck from supporting elements, potential collapse, and impairment of bridge functionality.
- **Failure Mechanism:** Rotating forces generated during an earthquake, particularly in curved or skew bridges, can result in deck unseating. This may occur due to insufficient seat length, bearing failure, or large displacement of the substructure.

Arch Buckling:

- **Impact:** Buckling of arches, leading to total failure or local damage in arch bridges.
- **Consequence:** Structural failure, potential collapse, and compromise of arch bridge integrity.

- **Failure Mechanism:** Buckling of arches due to seismic forces, potentially leading to total failure or localized damage. Inadequate shear keys in spans with hinges can also contribute to damage in the arch bridges.

In addition to these failure types, it is crucial to consider the historical evolution of seismic design codes. The impact of seismic events has led to the continuous refinement of these codes to enhance the resilience of bridges. However, the limitations in predicting earthquake behaviour and the potential for new vulnerabilities to emerge after each event highlight the challenges in achieving complete protection against future damage.

The history and evolution of seismic design codes for different countries indicate a continuous effort to improve standards based on lessons learned from past earthquakes. This ongoing process emphasizes the importance of research, development, and the incorporation of new findings into design practices to enhance the seismic resilience of bridges worldwide.

Understanding these failure mechanisms is crucial for seismic engineers and designers to develop effective countermeasures and enhance the seismic performance of bridges. Improving structural detailing, ensuring proper shear resistance, designing resilient bearings, and addressing issues related to ground movement are some of the key aspects in mitigating these failure mechanisms. Additionally, incorporating lessons learned from historical seismic events into the evolution of seismic design codes is essential for continuous improvement in bridge resilience.

2) **Flooding** ^[3]:

Flooding hazards can have severe and varied impacts on bridges, affecting their structural integrity, stability, and overall functionality. The interaction between bridge failure due to seismic events and flooding hazards would require detailed engineering analysis and consideration of specific site conditions. Additionally, the design and construction of bridges in flood-prone areas typically involve considerations for flood loads and hydraulic forces to ensure resilience against both seismic and flooding hazards.

Here are some common failure impacts on bridges caused by flooding hazards:

Foundation Erosion:

- **Impact:** Flooding can erode the foundations of bridges, especially those with shallow footings or situated in areas with loose soil. This erosion weakens the support structure and can lead to foundation failure.
- **Consequence:** Weakened foundations can lead to settlement, tilting, or even collapse of the bridge. Structural stability compromised, affecting overall functionality.
- **Failure Mechanism:** Flooding can erode the foundations of bridges, especially those with shallow footings or situated in areas with loose soils.

Scouring Around Piers and Abutments:

- **Impact:** Fast-flowing floodwaters can cause scouring around bridge piers and abutments. This scouring undermines the structural support, potentially leading to the collapse of bridge elements.
- **Consequence:** Scouring undermines structural support, potentially leading to the collapse of bridge elements. This can result in partial or total failure of the bridge.
- **Failure Mechanism:** Fast-flowing floodwaters cause scouring around bridge piers and abutments.

Hydraulic Forces and Structural Loading:

- **Impact:** Floodwaters exert hydraulic forces on bridge components, such as piers and abutments. This additional loading can exceed the design capacity, causing structural damage or failure.
- **Consequence:** Excessive hydraulic forces can cause structural damage or failure. Piers and abutments may not withstand the additional loading, compromising the bridge's integrity.
- **Failure Mechanism:** Floodwaters exert hydraulic forces on bridge components, such as piers and abutments.

Deck Submersion and Buoyancy:

- **Impact:** Submersion of the bridge deck in floodwaters can lead to buoyancy issues. Buoyant forces acting on the submerged structure can result in deck uplift, potentially causing the bridge to float and/ or become dislodged.
- **Consequence:** Buoyant forces on the submerged deck can lead to uplift, potentially causing the bridge to float and/or become dislodged. This disrupts the functionality and safety of the bridge.
- **Failure Mechanism:** Submersion of the bridge deck in floodwaters causes buoyancy issues.

Substructure Damage, Flood Vulnerability, and Lateral Loads from Flooding:

- **Impact:** Large displacements of substructures, as mentioned in the seismic damage types, might weaken the foundation of the bridge, making it more susceptible to damage from flood-related forces, such as strong currents or debris. Scour, defined as the erosion of streambed or bank material, is a significant contributor to bridge failures. Flood-induced scour can lead to substructure failure, especially in foundations not designed to resist scour depths. Design of bridges considers lateral loads caused by significant flooding events, such as those resulting from debris or floodwater impact. Failure to account for such extreme lateral loads can lead to substructure failure.
- **Consequence:** Failure to resist lateral loads can lead to substructure failure, influencing overall bridge stability.
- **Failure Mechanism:** Large displacements of substructures during flooding weaken the bridge's foundation.

Material Deterioration:

- **Impact:** Prolonged exposure to floodwaters can accelerate the deterioration of materials, especially if the water carries debris, sediments, or corrosive substances. This can compromise the strength and integrity of various bridge components.
- **Consequence:** Accelerated material deterioration compromises the strength and integrity of various bridge components, potentially leading to reduced load-bearing capacity and structural failure.
- **Failure Mechanism:** Prolonged exposure to floodwaters accelerates the deterioration of materials, especially if the water carries debris, sediments, or corrosive substances.

Impact from Floating Debris:

- **Impact:** Debris carried by floodwaters, such as trees, branches, or other large objects, can collide with bridge elements. This impact can cause structural damage, particularly to vulnerable sections like piers and superstructure elements.
- **Consequence:** Collision with debris can cause structural damage, particularly to vulnerable sections like piers and superstructure elements. This compromises the safety and functionality of the bridge.
- **Failure Mechanism:** Debris carried by floodwaters, such as trees or branches, collide with bridge elements resulting in severe damage and breakages at times leading to local failure.

Submersion-Related Corrosion:

- **Impact:** Submersion in floodwaters can lead to corrosion of metal components, including steel reinforcement and structural elements. Corrosion weakens the material and may result in reduced load-bearing capacity.
- **Consequence:** Corrosion weakens metal components, including steel reinforcement, leading to reduced load-bearing capacity. This compromises the overall structural integrity of the bridge.
- **Failure Mechanism:** Submersion in floodwaters leads to corrosion of metal components, including steel reinforcement and structural elements.

Embankment and Approach Erosion:

- **Impact:** Flooding can erode embankments and approaches leading to the bridge. The loss of support on approach roads can result in settlement, tilting, or even collapse of the bridge.
- **Consequence:** Erosion of embankments and approaches can lead to settlement, tilting, or collapse of the bridge. Loss of support on approach roads impacts functionality and safety.
- **Failure Mechanism:** Flooding erodes embankments and approaches leading to the bridge.

Reduction in Frictional Resistance:

- **Impact:** Floodwaters may introduce sediments and debris onto the road surface, reducing frictional resistance. This can contribute to vehicular accidents and affect the overall safety of the bridge.
- **Consequence:** Reduced frictional resistance on the road surface contributes to vehicular accidents, influencing the safety and usability of the bridge.
- **Failure Mechanism:** Floodwaters introduce sediments and debris onto the road surface, reducing frictional resistance.

Disruption of Infrastructure and Utilities:

- **Impact:** Flood-related failures may also disrupt the supporting infrastructure and utilities associated with the bridge, such as power lines, signalling systems, and communication networks.
- **Consequence:** Disruption of supporting infrastructure and utilities, such as power lines and signalling systems, can hinder overall transportation functionality and safety.
- **Failure Mechanism:** Flood-related failures disrupt supporting infrastructure and utilities associated with the bridge.

Operational Disruption:

- **Impact:** Flood-related failures can lead to the closure or restriction of bridge usage, disrupting transportation networks and influencing local communities and economies.
- **Consequence:** Closure or restriction of bridge usage disrupts transportation networks, influencing local communities and economies.
- **Failure Mechanism:** Flood-related failures lead to the closure or restriction of bridge usage.

Pounding Damage and Flood Effects:

- **Impact:** Pounding damage on abutments, particularly in combination with large displacement of substructure, might contribute to vulnerabilities during flooding. The impact of pounding can affect the overall stability of the bridge during flood events.
- **Consequence:** Pounding damage, especially in combination with large substructure displacements, contributes to vulnerabilities during flooding. This can affect the overall stability of the bridge.
- **Failure Mechanism:** Pounding damage on abutments, especially when combined with large substructure displacements, contributes to vulnerabilities during flooding.

Overall Structural Resilience:

- **Impact:** The ability of a bridge to withstand flooding hazards determines its overall structural resilience. Damage to superstructure, failures in piers, or other structural elements can compromise the bridge's ability to resist not only seismic forces but also flooding forces.

- **Consequence:** Compromised overall structural resilience due to damage in superstructure, failures in piers, or other structural elements. This compromises the bridge's ability to resist both seismic and flooding forces, influencing its safety and functionality.
- **Failure Mechanism:** The ability of a bridge to withstand flooding hazards linked to its overall structural resilience. Minor or moderate distress in foundation/ piers can lead to increased deterioration in such elements causing local failure in those elements.

To mitigate these risks, bridge designs in flood-prone areas often incorporate features such as increased elevation, scour protection measures, and materials resistant to water-induced deterioration. Additionally, proper maintenance and early warning systems can help minimize the impact of flooding hazards on bridges.

3) Cyclones ^[4]:

The impact of cyclones on structures and infrastructure can be severe, resulting in various types of damage. The following types of damage along with the potential impacts are:

High Wind Loading:

- **Impact:** Excessive wind loading may lead to structural failure, especially in vulnerable sections.
- **Consequence:** Collapse of bridge spans, loss of functionality, and potential risk to public safety.
- **Failure Mechanism:** Inadequate design for wind resistance, leading to structural failure under high wind loads.

Storm Surge and Coastal Erosion:

- **Impact:** Storm surges and coastal erosion can undermine bridge foundations and cause structural instability.
- **Consequence:** Foundation failure, structural misalignment, and potential collapse, affecting overall bridge stability.
- **Failure Mechanism:** Erosion of soil around bridge foundations, leading to compromised stability.

Heavy Rainfall and Flooding:

- **Impact:** Heavy rainfall and flooding can result in submersion of bridge components and scouring around foundations.
- **Consequence:** Structural damage, loss of load-bearing capacity, and potential collapse.
- **Failure Mechanism:** Scouring around foundations due to heavy rainfall, compromising the bridge's structural integrity.

Debris Impact:

- **Impact:** Flying debris during a cyclone can collide with bridge elements, causing damage.
- **Consequence:** Structural damage, potential collapse, and impairment of bridge functionality.
- **Failure Mechanism:** Impact from flying debris, leading to structural failure in vulnerable areas.

Tidal Surge:

- **Impact:** Higher than normal tides during cyclones can lead to tidal surges, submerging bridge components.
- **Consequence:** Submersion of critical bridge elements, potential corrosion, and degradation of materials, leading to long-term structural issues.
- **Failure Mechanism:** Corrosion and degradation of materials due to prolonged exposure to saltwater.

Dynamic Loading from Wind-Induced Vibrations:

- **Impact:** Wind-induced vibrations can subject the bridge to dynamic loading, especially in tall or slender structures.
- **Consequence:** Fatigue failure, structural resonance, and potential collapse due to excessive dynamic loading.
- **Failure Mechanism:** Inadequate design for wind-induced vibrations, leading to fatigue failure over time.

Soil Liquefaction:

- **Impact:** Intense cyclonic activity can cause soil liquefaction around bridge foundations.
- **Consequence:** Settlement and tilting of bridge support, compromising structural stability.
- **Failure Mechanism:** Changes in soil structure and density due to water saturation, leading to reduced bearing capacity.

Lightning Strikes:

- **Impact:** Cyclones often accompanied by intense thunderstorms, increasing the likelihood of lightning strikes on bridges.
- **Consequence:** Structural damage, potential fire hazards, and impairment of electrical systems.
- **Failure Mechanism:** Direct lightning strikes causing localized damage or ignition of combustible materials.

Temperature Extremes:

- **Impact:** Cyclones can bring extreme temperature variations, affecting the thermal expansion and contraction of bridge materials.

- **Consequence:** Thermal stress, expansion joint failures, and potential structural deformation.
- **Failure Mechanism:** Inadequate consideration of temperature extremes in bridge design, leading to material fatigue.

Sediment Transport and Deposition:

- **Impact:** Cyclone-induced flooding can transport and deposit sediment, affecting bridge foundations and waterway navigation.
- **Consequence:** Accumulation of sediment around bridge piers, compromising stability and hindering water flow.
- **Failure Mechanism:** Sediment deposition causing scouring or increased lateral forces on bridge supports.

In addition to these damage types, it is crucial to consider the historical evolution of cyclone-resistant design codes. The impact of cyclonic events has led to the continuous refinement of these codes to enhance the resilience of structures and communities. However, challenges remain in predicting and mitigating the impacts of cyclones, especially in the changing climate conditions.

The history and evolution of cyclone-resistant design codes for different regions indicate a continuous effort to improve standards based on lessons learned from past cyclones. This ongoing process emphasizes the importance of research, development, and the incorporation of new findings into design practices to enhance the cyclone resilience of structures and infrastructure.

Understanding these damage mechanisms is crucial for engineers and designers to develop effective countermeasures and enhance the cyclone resilience of buildings and infrastructure. Improving wind-resistant design, implementing robust coastal protection measures, enhancing drainage systems, and addressing issues related to slope stability are some of the key aspects of mitigating the impacts of cyclones.

4) Landslide ^[5]:

Landslide failure in bridges refers to the structural damage or collapse of a bridge resulting from a landslide event. A landslide is the downward movement of rock, soil, and debris on a slope, and when it affects a bridge, it can lead to various failure modes.

Foundation Instability:

- **Impact:** Bridge foundations may experience settlement, tilting, or complete failure.
- **Consequences:** Foundation settlement, tilting, or complete failure, compromising the overall structural integrity of the bridge.
- **Failure Mechanism:** Landslides can alter the stability of the ground beneath the bridge, leading to foundation instability.

Slope Movement and Scouring:

- **Impact:** Slope movement and scouring can lead to undermining of the bridge foundations.
- **Consequences:** Scouring undermines the support structure, potentially causing structural failure. Slope movement can induce lateral forces on the bridge, leading to displacement or collapse.
- **Failure Mechanism:** Landslides can result in slope movement and scouring around bridge foundations.

Debris Impact:

- **Impact:** Debris generated by landslides can impact bridge elements.
- **Consequences:** Structural damage, including deformation or failure of bridge components, due to the impact of debris.
- **Failure Mechanism:** Landslides often generate debris, which can impact bridge elements.

Superstructure Damage:

- **Impact:** Landslide-induced ground movement can cause damage to the bridge superstructure.
- **Consequences:** Structural damage to beams, girders, or the deck, potentially leading to partial or total collapse of the bridge.
- **Failure Mechanism:** Landslide-induced ground movement can cause deformation or failure in the superstructure.

Pier and Abutment Overturning:

- **Impact:** Lateral forces from landslides can cause the overturning of piers and abutments.
- **Consequences:** Overturning of piers and abutments, compromising the stability of the bridge and leading to collapse.
- **Failure Mechanism:** Landslides can exert lateral forces on piers and abutments.

Soil Erosion and Settlement:

- **Impact:** Soil erosion around bridge foundations can lead to settlement.
- **Consequences:** Settlement of foundations, which can lead to misalignment, tilting, or collapse of the bridge.
- **Failure Mechanism:** Landslides may result in soil erosion around bridge foundations.

Bridge Displacement:

- **Impact:** Landslide-induced ground movement can cause lateral displacement of the entire bridge.
- **Consequences:** Structural damage or collapse due to the displacement of bridge elements.

- **Failure Mechanism:** Landslide-induced ground movement can cause lateral displacement of the entire bridge.

Reduction in Load-Bearing Capacity:

- **Impact:** Altered load-bearing capacity of the soil beneath the bridge.
- **Consequences:** Reduced load-bearing capacity, potentially leading to structural failure under normal loading conditions.
- **Failure Mechanism:** Landslides can alter the load-bearing capacity of the soil beneath the bridge.

Sedimentation and Blockage:

- **Impact:** Sedimentation or blockage of waterways under the bridge.
- **Consequences:** Increased hydraulic pressure on the bridge elements, potential scouring, and compromised structural stability.
- **Failure Mechanism:** Landslides may result in sedimentation or blockage of waterways under the bridge.

Loss of Connectivity:

- **Impact:** Complete or partial collapse of the bridge.
- **Consequences:** Loss of connectivity, disruption of transportation networks and potentially isolating communities.
- **Failure Mechanism:** Complete or partial collapse of the bridge due to landslide-induced damage.

Risk to Life and Property:

- **Impact:** Landslide-induced bridge failure poses a safety risk.
- **Consequences:** Potential loss of life, injuries, and damage to surrounding structures and infrastructure.
- **Failure Mechanism:** Landslide-induced bridge failure poses a risk to the safety of people and property.

Landslide failures can lead to severe consequences for bridges, influencing their structural stability, functionality, and safety. The effects range from structural damage to complete collapse, with implications for transportation networks and community well-being. Mitigation measures, including proper geological assessments, structural design considerations, and maintenance practices, are essential to minimize the impact of landslide failures on bridges.

C) Deterioration process in bridges [6,7,8,9,10,11,12]

Visual indicators stand as the frontline signals, providing engineers with tangible cues about the structural health of a bridge. This subsection delves into the nuanced details of surface cracks, corrosion, and spalling—prominent visual manifestations that serve as early warnings of deterioration. Understanding these visual indicators is crucial for engineers as they embark on the assessment journey,

using these cues as a starting point for comprehensive evaluations and the formulation of targeted mitigation strategies.

Surface cracks on the bridge components, such as the deck, abutments, or piers, are among the most conspicuous signs of deterioration. These cracks can take various forms, including hairline cracks, spider web patterns, or more severe fractures. The formation and progression of surface cracks often result from a combination of factors, including exposure to environmental elements, cyclic loading, and material aging.

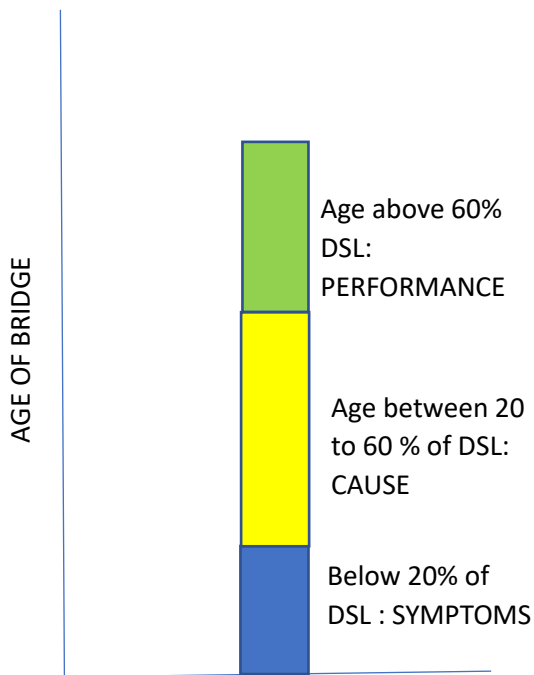
All bridge structures have a very predominant deterioration process. During the early years, symptoms observed indicate the start of deterioration process. Based on the Design Service Life [DSL] the early age is below 20 percentage of DSL, symptoms are sufficient indicators of deterioration. Symptoms that are most pronounced include crazing, cracking (minor to severe), delamination, spalling, deformities, rust stains, and porosity.

Beyond this period (20% of DSL), symptoms alone may not identify correctly the deterioration model. Identification of Cause of deterioration is essential. Various early age symptoms may help to identify the Principal Cause. There could be multiple causes, which manifest the entire deterioration model. EN1504 researched and published in Nineties; define three main processes that can result in deterioration in concrete. The defined processes are

- a) Mechanical process
- b) Physical process
- c) Chemical process

These three Cause processes further divided into 11 Causes. These 11 causes entirely define the deterioration model of the concrete structures. Multiple causes can contribute towards the deterioration model. The most prominent of the cause defined as the Principle Cause and other causes are the secondary causes. Most of the time initial symptoms manifest into one of the cause. This manifestation occurs as the age of the bridge structure advanced. When age of the bridge structure is beyond 15 to percent of DSL, identification of cause is essential. Identification of Cause between 20 to 60 percent of DSL assists the inspection team.

Impact of aging in the bridge structure is pronounced when age of the bridge exceed 60 percent of DSL. Many a times, this impact is not visible immediately. Bridge inspection teams have then to rely on Short term monitoring of components of the bridge structure, which show persistent symptoms. Structural Health Monitoring [SHM] adopted for short durations (36 – 48 hours) and then repeated three to four times, at intervals of 3 to 4 months, reveal the decrement in performance. Past research in SHM have recognized that as deterioration progress, performance decreases.



The effect of repeated cyclic loading (overloaded at times), fatigue, and internal corrosion of embedded reinforcements all may not manifest to visible signs.

Monitoring of such aging bridges is the only method to access the realistic data related to the deterioration model. The existence of distress in bridge structure begins from day one. Internal and external factors results in propagation of distress. All existing bridges globally have this propagating distress. Every existing bridges are in varying stage of deterioration process. This degree of distress is dependent upon the age of bridge, geospatial location and exposure to environment. The propagation and level of distress is a clear definition of the deterioration model.

It is critical to understand the above-mentioned three stages in the life cycle of the bridge structure to focus on the effect of the action of the forces of natural hazards on existing bridge structures.

Each natural hazard has a typical force configuration that acts on the bridge structure. Increased severity of the hazard magnifies this force configuration on the bridge. The impact of such forces on the bridge structure is also very critically dependent upon the stage of the deterioration model of the bridge structure. When one has to evaluate the consequence of natural hazards on existing bridges, it is critical to understand and have clarity on how the forces of natural hazards will act on pre-existing deterioration model. This makes it essential to model varying deterioration stages and impose the force of natural hazard on the bridge structure. Results of this study will define the consequences of the hazard on the bridge structure.

D) Approach for Evaluation of Impact.

Lack of existing research or information regarding the impact of natural hazard forces on deteriorated bridges, to address this gap, a technical approach is being taken, involving the creation of a digital model. The technical aspect of this process involves:

1. Digital Model Creation: Deficient data related to the impact of natural hazard on deteriorated bridges makes it essential for research to determine the impact on a model. To be able to predict what will be the consequence in the future, due to the force of natural hazards on existing bridges showing distress, we have to resort to a digital model. Usage of design software applications clubbed and utilized with the application of experience within bridge management.

2. Incorporating Deterioration: Statistical data from Bridge management systems indicate globally aging bridges show varying degrees of deterioration. The

deterioration model indicates that distress is majorly located in a particular component of the bridge structure. Rare cases show uniform distress in every component. This information is the basis for our using individual components to evaluate the impact. In the Bridge sub-structure, piers show distress. In the Superstructure, the distress is in the girders. The predominant deterioration symptoms are various types of cracks, spalling, and deformation.

3. Forces Variation: The Bridge is located in a marine coastal area on a district road with a load capacity of **70R**. The bridge is located in **seismic zone 4**, has an average **precipitation of 1500mm** per year, and is prone to cyclones a minimum once a year with wind speed **intensity of 50 kms/hour**. The bridge has a 200-metre hillock on one side, exposing the bridge to a landslide of **100 cubic meter**. Maximum span length is **20 meters**. Pier shape in most cases is either circular or rectangular with hammerhead edges. The design of the component from design perspective stable for full live load and dead load conditions.

4. Analysis and Simulation: Digital modelling of Pier and "I shaped", Girder is done. These two components show distress symptoms in the form of cracks, degradation of concrete due to distress.

a) For Pier, the size assumed is 2500mm X 750 mm with full hammerhead edges at either ends or circular pier of 1200 diameter. The height assumed is 10000 mm from the top of the pile cap to the bottom of the pier cap. The shape and dimensions of the pier kept the same for all types of force application.

b) For "I-shaped" Girders, the size assumed are typically 1500 mm deep, the top flange is 1200 mm, and the bottom flange is 700 or 900mm. The web thickness is 250 mm.

c) Data Collection and Interpretation: The data relating to the behaviour of the component (pier or girder) assumed based on their probability of failure occurring by one the failure mechanism that is possible during occurrence of the natural hazard. Only one type of natural hazard will be acting on the bridge at a given time. The structural capacity evaluation based on standard Indian codes of design (IS 456) for concrete structures. Simple reinforced sections assumed. Forces due to natural hazard acting on pier or girder as also calculated as per defined method under various applicable codes of design.

The dimension of the crack for the first cycle of experiment is minor in nature. Cracks are assumed for the experiment to be on one face initially and then on the face perpendicular to that face subsequently. The location for the first cycle is near the support or within a third of the longer dimension. Subsequently, the crack is in the middle third area of the component. For the experiment, the minor crack will change to a major crack **in two** increments. The inclination for subsequent cycle altered at all locations. The force applied by natural hazards will be initially for earthquakes of magnitude 5.0 on Richter scale progressively increasing by 1.0 until it reaches 9.0 on the Richter scale. Apply this force for all cases, locations, and severity of cracks. Subsequently subject, all cases, locations, and severity of cracks to force due to flooding starting from 500 mm overtopping, increasing progressively by 250 mm until 1500mm of overtopping occurs. Similar repeat the experiment for force due to increasing cyclones and landslides. The aim of this experiment is to evaluate at what force application due to natural hazards does

the component fails. Evaluate for every case, location, and severity of the crack, the force required for failure. Failure of the component is either a rupture or deformity that considered a failed state. Based on the above-stated objectives, variable bridge components, and distress characteristics, the following different types of evaluations emerge.

Component	Support conditions	Distress characteristics
Girder I shaped	One end SS, other continuous	Minor crack located on the bottom flange/side, within 1/3 distance of the support, perpendicular to the bridge
		Minor crack located on the bottom flange/side, within 1/3 distance of the support, parallel to the bridge
		Minor crack located on the bottom flange/side, within 1/3 distance of the support, inclined to the bridge
		Intermediate Crack located on the bottom flange/side, within 1/3 distance of the support, perpendicular to the bridge
		Intermediate Crack located on the bottom flange/side, within 1/3 distance of the support, parallel to the bridge
		Intermediate Crack located on the bottom flange/side, within central 1/3 of the bridge, inclined to the bridge
		Major Crack located on the bottom flange/side, within 1/3 distance of the support, perpendicular to the bridge
		Major Crack located on the bottom flange/side, within 1/3 distance of the support, parallel to the bridge
Major Crack located on the bottom flange/side, within central 1/3 of the bridge, inclined to the bridge		
Girder I shaped	One end SS, other continuous	For all crack type and orientation, change the location to the side of the girder (instead of bottom).

REPEAT CYCLE SIMILAR TO ABOVE CYCLE BUT FOR DIFFERENT SUPPORT CONDITION ARE ATTEMPTED

Once the failure pattern for cracking identified, similar cycles repeated for other symptoms like loss of section, deformation, etc.

The results will indicate the force of natural hazard essential for failure of the single component for a given configuration of crack or any other symptom.

Methodology for Determining Bridge Collapse Threshold

1. Inventory and Assessment of Bridge Components

- **Component Identification:** Catalog all critical components of the bridge, such as piers, girders, bearings, etc.
- **Determine Distress Levels:** Assign distress levels to each component based on the existing data (e.g., minor, intermediate, major).

2. Calculation of Dead Load

- **Bridge Load Analysis:** Calculate the total dead load of the bridge. This includes the weight of the bridge itself, along with any non-movable objects or permanent fixtures.
- **Load Distribution:** Understand how this load distributed across the different components of the bridge.

3. Evaluation of Non-Distressed Components

- **Axial Capacity Assessment:** For each non-distressed component, assess its axial load-carrying capacity. This should be based on current standards and consider factors like material strength, age, and environmental influences.
- **Cumulative Capacity Calculation:** Calculate the cumulative axial capacity of all non-distressed components. This gives you the total load-bearing capacity of the structurally sound parts of the bridge.

4. Comparative Analysis for Collapse Determination

- **Comparison of Loads and Capacities:** Compare the total dead load of the bridge with the cumulative axial capacity of non-distressed components.
- If the cumulative axial capacity is greater than or equal to the dead load, the bridge considered to have structural integrity.
- If the cumulative axial capacity is less than the dead load, it indicates a risk of collapse.

5. Incremental Analysis of Distressed Components

- **Gradual Increase in Distress:** Systematically increase the number and severity of distressed components in your model. After each increment, reassess the cumulative axial capacity of the remaining non-distressed components.
- **Threshold Identification:** Identify the point at which the addition of distressed components causes the cumulative axial capacity to fall below the dead load. This point marks the critical threshold for potential collapse.

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GABM & GARM GLOBAL ANALYTICS FOR BRIDGE MANAGEMENT AND GLOBAL ANALYTICS FOR RESILIENCE AND RISK MANAGEMENT

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A) ABSTRACT:

Chapter Four of the whole document is a chapter that outlines the various technologies used in the evolution of Global Analytics for Bridge Management [GABM] and Global Analytics for Resilience and Risk Management [GARM]. Further, it incorporates the details of the approach adopted to evaluate the response of the existing deteriorated bridges to the force of natural hazard. Essentially certain assumptions incorporated simplify the approach. These assumptions ensure attainment of the results leading to our goals. The assumption relates to the geometry (shape, size, length) of the components in the bridge, application of dead loads and live load combinations. Finally, the application of forces due to natural hazard are restricted to severe category only. Further refinements are possible. Response of the fraternity to the technique, its usage will determine the level of refinements introduced. The present findings indicate the requirement of the level of force to act on the deteriorated bridge, which will result in the bridge deemed as non-usable. The outcome of using GARM in combination with GABM ensures identification of the possibility of the bridge surviving or failing with the occurrence of the natural hazard. For every bridge, analysis reveal the level of severity the deteriorated bridge is able to sustain. This knowledge enables activation of actions essential to restore resilience in the bridge.

B) INTRODUCTION TO GABM AND GARM

The evolution of Global Analytics for Bridge Management [**GABM**] is the culmination of over 25 years of research. The first indigenous system evolved was the Indian Bridge Management System [IBMS] which was implemented by the Ministry of Road, Transport and Highways [MORTH], Government of India from 2015 to 2019. IBMS achieved the distinction of being the First Digitized bridge management system, the largest database of bridges owned by a single owner with data accumulated over multiple cycles of inspection for over 140,000 bridge structures. IBMS evolved into Unified Bridge Management System [UBMS]. UBMS had two deterioration modelling algorithm. One based on Symptoms and the other based on Cause of distress. Both IBMS and UBMS are online systems with database stored on cloud server. They were ideal for owners of large database of bridges on their network. IBMS and UBMS are not suitable for owners with Micro database of say 50 bridges. This made IBMS and UBMS out of reach for Municipal Corporations,

local office of highway authority, regional authorities and fragments of highway network. A smaller system was essential. Evolution of GABM fulfil these requirements.

GABM utilizes all the technologies evolved during IBMS and UBMS. These technologies are time tested, validated during implementation on various networks for over 200,000 bridge structures from 2015 to 2021.

GABM is a Stand-alone Android application, installed on single Android device, working in an internet free environment. Cost efficiency of GABM proves its viability for owners of micro inventory of bridges. Bridge Management applicability for a 50-bridge inventory is feasible. GABM usage for 50 to 200 bridges on any network ensure last mile applicability of Bridge Management.

Global Analytics for Bridge Management (GABM) is a comprehensive platform designed to aid in the management of bridges globally. It utilizes advanced analytics to assess the condition of bridges, predict maintenance needs, and optimize resource allocation for bridge management.

The various modules in GABM assist in evaluation of results that help to ensure all objectives of bridge management are satisfied.

The Modules in GABM are:

- **Data Management Module:** This module handles the collection, storage, and organization of bridge-related data, including structural information, inspection reports, and maintenance records.
- **Analysis and Assessment Module:** This module performs in-depth analysis and assessment of bridge conditions, utilizing data-driven approaches to identify vulnerabilities, predict deterioration, and prioritize maintenance activities.
- **Resource Optimization Module:** This module optimizes resource allocation for bridge management, considering factors such as budget constraints, maintenance priorities, and risk levels to maximize the efficiency and effectiveness of maintenance efforts.
- **Functionalities of GABM:** The main functionalities of GABM involve using

Standard Costs applicable for specific year. These standard costs are required to be available within GABM before any bridge is analysed for that year. User will need to input the standard costs for all the years for before starting analysis of bridges.

Import of Data: GABM allows users to import data associated with bridge inspection, maintenance activities using standardized formats, facilitating easy integration of information across various bridge management platforms.

Export of Data: GABM enables users to export data generated from analyses, assessments, and resource optimization processes for

reporting purposes or further analysis in external tools or systems. This functionality enhances interoperability and allows for seamless integration with software solutions in GARM

GABM's distinct modules, cater to the following main algorithms^[1]

- a) Evaluation of Deterioration progression in the bridge.
- b) Evaluation of Balance service life.
- c) Life Cycle Cost Analysis.
- d) Risk assessment for Four natural hazards.
- e) Priority and ranking for Fund optimization.

Basis for the technical algorithms used in the above critical evaluations are theories evolved and perfected in basic science many year ago.

- a) Evaluation of Deterioration progression** in the bridge relies on the following two modelling techniques:
- i. Deterministic model
 - ii. Stochastic model

GABM deploys both the Deterioration Modelling techniques in evaluation of the deterioration progression in bridges. Usage of these techniques to develop bridge deterioration models based since late eighties and further evolved over the last 30 to 40 years^[2].

- i) Deterministic Model:** The Deterministic model assumes that the bridge tendency is certain, so usage of regression analysis determines the decay rate. This model is dependent on mathematical or statistical formula for the relationship between the factors and affecting bridge deterioration and measures the bridge condition. Developed models uses straight-line extrapolation as well as by regression and curve fitting methods. Generates Curve fitting graph using regression equation between average ages of Bridge Vs Ratings. Graph plotted for Integral & Non-Integral Deck, Superstructure, Substructure and Scour as per state wise. Output is to find Average transition period.
- ii) Stochastic Model^[3]:** Stochastic models treat the bridge deterioration process as one or more random variables. This makes stochastic models inherently more capable of capturing the uncertainty and randomness of the deterioration process than deterministic models. Classified discrete-time models are either state-based or time-based. In state-based models, the modelled deterioration process through a probability of transition from one condition state to another state in a discrete time. Given that, the deterioration process is dependent on a set of measurable variables such as annual average daily traffic (AADT), climate, age, etc. In these models, extensive usage of Markov chains (evolved in 1906) has application. Two years data on condition state uses Markov chain algorithm to determine the deterioration model. Condition states for Integral & Non-Integral Deck, Superstructure, Substructure and Scour utilized. Outcome of this model determines the probability of chance to move to higher level of distress from a lower level of distress. Generated is the estimation of Transition Probability Matrix (TPM). This assists in evaluation of Balance service life of the bridge.

b) Evaluation of Balance service life:

Balance service life evaluation based on Deterioration Cause Matrix. This matrix classified into Mechanical causes, Physical causes, and Chemical causes.

Evaluation entails scrutiny of Structural condition ratings collected by field engineer for the structural components such as integral & Non-Integral deck, Superstructure, Substructure and Scour. Only if Structural Rating is greater than "3" for any of the components, then usage of cause rating for each component possible. Based on cause ratings, generating cause matrix to find deterioration rate. Time 'T' taken for deterioration based on Probability for all three cause-rating values, and average ratings for all three causes^[4]. Based on Markov analysis year of deterioration will vary and the least value from the results obtained. Research in Europe to compile EN 1504 adopted in the definition of cause matrix and the subsequent analysis.

c) Life Cycle Cost Analysis [LCC analysis]

The Ministry of Defence of United State of America first introduced LCC analysis in in early 1960's. Since then it has been adapted for various purposes. In mid-nineties, the Federal Highway Administration [FHWA] proposed LCC usages for bridges. Slowly many countries adopted LLC analysis within Bridge management also. LCC underscores the significance of bridge management for sustainable infrastructure, with a focus on aging structures. Within GABM, we emphasizes the need for Life Cycle Cost Analysis (LCCA) with real-time information based on dynamic, robust and real time information. The methodology integrates LCCA into Bridge Management, considering tangible and intangible costs. GABM integrates deterioration model application to LCCA. This result in reliable accurate information regarding progression of deterioration accounted within LCCA^[5]. LCCA offers a selection tool for the adaptation of the most cost efficient design for rehabilitation. The basis of incorporation of tangible and non-tangible parameters in GABM is Socio-Economic parameters in GABM.

d) Risk assessment for four natural hazards^[6].

- i. Earthquakes:** Earthquakes pose a significant risk to bridge structures due to their sudden and unpredictable nature. Risk assessment involves evaluating the probability of seismic events occurring in a specific region, considering factors such as historical seismic activity, tectonic plate movements, and geological characteristics. Intensity and proximity to fault lines are crucial factors in determining the potential impact on bridges. Mitigation strategies may include retrofitting measures, such as base isolation or strengthening vulnerable components.
- ii. Floods:** Bridges located near rivers or in flood-prone areas are vulnerable to flooding, which can cause erosion, scouring, and structural damage. Risk assessment for floods involves analysing historical flood data, river discharge patterns, topographic features,

and climate change projections. Vulnerability assessments consider bridge elevation, hydraulic capacity, and drainage systems. Mitigation measures may include raising bridge elevations, improving drainage, and installing flood barriers or scour protection.

- iii. Landslides:** Bridges situated in mountainous or hilly terrain are at risk of landslides, which can destabilize bridge foundations and abutments. Risk assessment includes mapping landslide-prone areas, and analysing slope stability, rainfall patterns, and geological conditions. Vulnerability assessments evaluate bridge design and construction methods to withstand landslide impacts. Mitigation strategies may involve slope stabilization measures, such as retaining walls, rockfall barriers, or vegetation management.
- iv. Cyclones:** Bridges located in coastal regions are susceptible to high winds, storm surges, and heavy rainfall associated with hurricanes or cyclones. Risk assessment considers historical storm data, wind speed probabilities, coastal erosion rates, and floodplain mapping. Vulnerability assessments focus on bridge exposure, structural resilience, and evacuation routes. Mitigation measures may include strengthening bridge superstructures, enhancing coastal defences, and implementing emergency response plans.

Methodology for Risk Assessment:

GABM integrates data input by the user related to the historical hazards occurrence, severity and the impact on the geographical region. This historical data related to the specific hazard helps in evaluation of risk index of the region. Risk assessment modelling quantify risk hazard. Consideration is given to factors like risk probability, intensity, proximity to recent past occurrence [7, 8]. Integration of regional risk index with the information relating the distress in various bridge components provides the vulnerability of the bridge to the risk hazard. This methodology assists in prioritization of resource allocation. Prioritised bridges on the most critical route connecting various regional areas with the location of importance (hospitals, relief centres). Proactive remedial measures implemented on such bridges render resilience to such bridges.

By incorporating risk assessment and mitigation modules, bridge managers can enhance the sustainability and safety of critical transportation infrastructure, ensuring efficient resource allocation and proactive management of natural hazard risks.

e) Priority and ranking for Fund optimization:

GABM relies on the evolved concept of "First Repair Worst Damage" [**FRWD**] introduced to Disasters and Distress management in 1992. Since the introduction of the concept, many other countries have also adopted the same. Integration of FRWD concept with the ratings of bridge management provides a sound algorithm for priority and ranking procedure. Priority is determined based on observation for various rating numbers, including-

- i. Bridge Structural Ratings
- ii. Bridge Functional Ratings

iii. Socio-Economic Ratings

Calculation of Critical weightage (Cw), considers factors like integral-non-integral deck, superstructure, substructure, and scour efficiency.

Assignment of Importance weightage (Iw), considers type of road, loading, length of the bridge, span length, and average daily traffic.

Derived Wsum becomes the guiding factor for the decision-making process for repair interventions. It considers factors like the age of the bridge and cost comparison between repair and replacement.

The ranking system, known as RankBrig, incorporates Cw and Iw, ensuring bridges with severe distress are prioritized. The flow for priority and ranking, accounts for the consolidated data of multiple bridges, is multiple parameter dependent, integrates distress, and deterioration progression for decision-making in the bridge management system.

The ranking and priority protocol, adopts the "First Repair Worst Damage" philosophy initially and progressively transitions to "Repair at First Symptom" (FRWD to RAFS) as more bridges move to safe zones^[9].

GARM - Online Implementation:

Global Analytics for Resilience and Risk Management (GARM) focuses on enhancing resilience in infrastructure bridge structures in the network. Resilience and Risk management presently focuses on four natural hazards namely earthquakes, cyclones, flooding, and landslides. GARM employs sophisticated analytics to assess vulnerabilities, develop resilience strategies, and prioritize mitigation efforts^[4].

The duo of GABM and GARM applications work in tandem to achieve the dual objectives of bridge management and resilience enhancement. GABM functions in an internet free environment deployed on a laptop. Engineers can use GABM at bridge location for the inspection process. Data collected within GABM used to evaluate the basic results for bridge management objectives. GABM also provides critical information related and required for Enhancement of resilience in bridges. GARM utilizes all required data exported from GABM.

GARM is an online tool to ensure accessibility and real-time collaboration among stakeholders involved in resilience management efforts. GARM functions to analyse further the information from GABM to provide critical results, which enhances resilience in bridges.

The various modules within GARM functionalities depend on utilization of the data imported from GABM.

The four modules of GARM are:

- **Report Generation Module:**

Post conducting bridge inspection, results evaluated in GABM are essentially required for decision-making process. Multiple departments within the network management organization need to be involved in this decision-making process. To facilitate ease of access, the Report Generation Module of GARM provides all bridge management results formatted as a Bridge report. Being online, report is available across the organization.

- Risk Assessment Module:**
 This module assesses the potential risks posed to various bridges in a network, from various hazards such as earthquakes, floods, cyclone, and landslides. It evaluates Bridge Vulnerability Index and provides Bridge Risk Index for each of the hazard. The results provide critical inputs for resilience planning. The user department to rectify and eliminate the distress and deterioration in the bridge can initiate proactive actions. Elimination of deterioration help to usher and restore resilience and sustainability.
- Deterioration to Failure scenario Module:**
 Based on the structural status of the bridge during the current year, the module evaluates the probability of failure occurring in the bridge during the occurrence of the natural hazard. The modules basically proceeds from the level of deterioration in the bridge and determines the response of the bridges structure (deteriorated and degraded status) to the application of forces due to natural hazard occurrence based on the severity of the occurrence. The results of this module provide valuable inputs to the Bridge Resilience module. The results also can estimate the level of severity of natural hazards that can cause a failure in the bridge.
- Bridge Resilience Module^[10]:**
 This module facilitates the development of resilience strategies by identifying appropriate mitigation measures, considering factors such as cost-effectiveness, feasibility, and expected impact on infrastructure resilience. It also prioritizes resilience actions based on the severity of risks, the criticality of infrastructure assets, and available resources. It helps stakeholders allocate resources efficiently to address the most pressing resilience needs. It provides feedback to refine and adjust resilience efforts as needed to ensure continual improvement in infrastructure resilience.
 The most critical output of this module is the map-supported interface that assists the users to select the route to take to reach the zone of disaster from the present location. This user interface provides list of highways/ road that the user can take. It then displays of the list of bridges on this highway/ road. The user can select the bridges within the route to see the probability of bridge surviving the natural hazard.

C) BRIDGE INSPECTION BASIS FOR ANALYSIS

Bridge inspection serves as the foundation for analysing various parameters within the context of GABM (Global Analytics for Bridge Management). GABM is a systematic approach to managing bridge assets within a network, considering factors such as condition assessment, maintenance, and budgetary constraints.

Bridge inspections provide critical data and information that feed into the analysis process within GABM. These inspections involve visually assessing the condition of bridges, identifying structural issues, and evaluating various components such as decks, superstructures, substructures, and support systems^[11]. The data collected during inspections typically include structural integrity, deterioration, corrosion, and other relevant factors.

GABM, these inspection inputs are essential for analysing various parameters that influence decision-making. How these inputs contribute to the analysis:

- i. **Condition Assessment:** Inspection data forms the basis for assessing the overall condition of bridges within the network. This assessment involves quantifying the extent of deterioration, identifying potential hazards, and prioritizing maintenance or repair needs.
 - ii. **Structural Health Monitoring:** Bridge inspections provide crucial information for monitoring the structural health of bridges over time. By analysing trends in inspection data, engineers can detect signs of deterioration or structural weaknesses, allowing timely interventions to prevent further damage.
 - iii. **Risk Analysis:** Inspection inputs help in conducting risk analysis by identifying vulnerabilities and potential failure modes of bridges. This analysis considers factors such as traffic volume, environmental conditions, and the structural condition of the bridge to assess the likelihood and consequences of failure.
 - iv. **Performance Evaluation:** Inspection data used to evaluate the performance of bridges against established criteria or standards. By comparing inspection results with performance benchmarks, asset managers can identify underperforming bridges and allocate resources effectively.
- 5. Cost-Benefit Analysis:** Bridge inspection inputs are integral to conducting cost-benefit analyses for various maintenance and repair strategies. By quantifying the costs associated with different interventions and estimating the potential benefits in terms of improved safety and service life, decision-makers can prioritize investments and optimize resource allocation.

In GABM, budgetary constraints influence decision-making. Asset managers must make informed decisions on allocating limited resources to address the maintenance and repair needs of bridges within the network. Bridge inspection inputs provide essential information for prioritizing these decisions based on the criticality of infrastructure, risk factors, and available funding. Furthermore, the analysis of various parameters derived from bridge inspections informs bridge management decision-making by guiding the definition of remedial measures. These measures may include routine maintenance, structural repairs, rehabilitation, or replacement of bridges based on their condition and performance.

There is a need for a proactive approach to implementing these measures to ensure the safety and longevity of bridges on the network. Proactive maintenance and timely interventions can help mitigate risks, extend the service life of bridges, and optimize lifecycle costs.

Bridge Inspection inputs serve as the basis for analysing parameters within GABM, driving decision-making processes informed by budgetary constraints, and guiding the proactive implementation of remedial measures to ensure the safety and functionality of bridges within the network.

D) NAVIGATING FROM DETERIORATION TO FAILURE^[12]

Modes of Failure: (Earthquake)

Bridges affected by earthquake can fail due to various different mechanisms. The modes of failure, which our research has in focus, relates to those modes, which can possibly occur due to progression during an event occurrence

based on visible symptoms during the life of the bridge. Studies of bridge failures or collapses during earthquake in the past reveal that most cases of collapse occur due to failure of substructure (predominantly failure of piers), foundations failure, superstructure toppling, unseating and edge crushing. Most of the time the local failure of one component results in a cascading effect resulting in the whole bridge collapse. For Earthquakes, from many other modes only the following modes of failure are considered:

- i. Pier failure due to shear.
- ii. Superstructure unseating but not toppling.
- iii. Superstructure unseating and resulting in toppling due to poor support condition or failure of support after unseating.
- iv. Superstructure collapsing due to edge crushing.

Bridges collapse due to foundation failure resulting from distortion and bending. Failure of foundation can occur due to liquefaction of soil due to earthquake vibrations. Both these failures and collapses are not symptom dependant. We strict our research to the above mentioned symptom dependant modes.

- i. Pier failure due to shear.
Earthquake forces act in a sinusoidal manner. The force generated by the earthquake wave, which moves away from the epicentre to the periphery. The force intensity depends on the distance of the epicentre from the bridge. Farther the bridge from the epicentre less is the force intensity. This force acts horizontally on the piers. Characteristically based on the shear capacity, the pier will withstand the force or the pier will fail.
- ii. Superstructure unseating but not toppling.
Unseating of superstructure is also due to the sinusoidal nature of the force wave. At the maximum amplitude point, the whole bridge has moved up by a fraction. When the amplitude is vanishing and at its minimum, the bridge returns to the original state or moves down. This movement during the one wave cycle will repeat. The repetitions being equal to the number of wave cycles that the earthquake/ seismic force has. The superstructure (girder or beam) could get unseated from the original position over the bearing. If the unseating results in the beam or girder resting horizontally on the surface of the pier cap, lowering of the bridge span occurs by distance equal to the height of the bearing. This can cascade to other component failures.
- iii. Superstructure unseating and resulting in toppling due to poor support condition or failure of support after unseating.
The unseating impact can result in pier cap crushing. This crushing results in insufficient support to the girder or beam. Resultant toppling of the girder or beam occurs due to tilting of the girder or beam. This failure is typical when the wave moves perpendicular to the length of the bridge. Superstructure toppling can occur when the supporting pier or foundation topple. Superstructure toppling in this case is the cascading effect of support toppling.

- iv. Superstructure collapsing due to edge crushing.
When the earthquake wave is moving parallel to the length of the bridge, the wave action causes a forward push to the girder or beam. This forward push can result in crushing of weak edges when the beam or girder collide with the supporting adjoining component or next girder or beam. The presence of weakness in the periphery of the support location can result in this weakness resulting in failure. The edge failure will shorten the girder or beam and the same will fall downward due to loss of end support. Such failure will cascade into multiple spans failure if the girder or beam moving down also hits the pier and applies horizontal force on the pier. The force can result in pier collapse.

Modes of Failure: (Flooding)

Bridges affected by floods and earthquake can fail due to various different mechanisms. In the research, focus is on mechanisms that provide visible symptoms. For Flooding, the following modes of failure from many others are considered:

- i. Upstream bank erosion.
- ii. Loss of bearing arising from dislodgement or unseating of bearing.
- iii. Displacement of superstructure horizontally or due to vertical lifting and dislodgement post receding of flood waters.
- iv. Overloading due to debris on deck or superstructure.

Scoring is also one features that remains as a main cause of collapse of bridges in the flooding situation where velocity of water is very strong. For the above modes of failure/ collapse, various symptoms observed in the bridge structure are:

- i. Upstream bank erosion.
Historical evidence of bank erosion noted indicate continuous changes in the upstream banks and flow movement of river water. Any curvature in the river prior to approaching the bridge location is noted and record of velocity is studied.
- ii. Loss of bearing arising from dislodgement or unseating of bearing.
Any historical evidence of bearing pedestal concrete cracking noted is a symptom leading to possible bearing dislodgement. Post all previous floods, observations of the bearing location noted and record study will indicate possible danger for bearing dislodgement. Record of water velocity during the flood occurrence is an indicator for possible unseating that can occur. Any instance of bearing pedestal concrete cracking, which has remained unattended, will lead to possible dislodgement.
- iii. Displacement of superstructure horizontally or due to vertical lifting and dislodgement post receding of flood waters.
Historical data on the water velocity in India indicates that Ganges and its tributaries have the maximum velocity of 4m/s in the Gangetic planes. In the higher elevation region of Himachal Pradesh,

Uttarakhand velocity recorded previously observed to be in the range of 4m/s reaching maximum of 9m/s. The wave action of the floodwater may cause vertical uplifting of bridge deck, rendering it susceptible for horizontal movement due to velocity. When velocity of water is high during floods, the water carries sedimentation up to 30 to 50 percent.

- iv. **Overloading due to debris on deck or superstructure.**
Loading on the bridge deck and superstructure is normally the combination of live and dead load on the bridge. When water stagnates during flooding and this water is above the deck level of the bridge, it results in additional loading on the deck and superstructure. Water levels recorded over bridge deck can reach over 2.0 meters. Live loads imposed on the bridge due to traffic is not present during such high floods. Bridge experience horizontal force due to high concentration of sediments in fast flowing water. Wave action complicate the situation. Uplift force experienced is also critical.

Modes of Failure (Landslide):

Landslides can occur due to various factors and can exhibit different modes of failure depending on the underlying mechanisms and triggering events. Here are some common types of landslides:

- i. **Rotational Landslides (Slumps):** In rotational landslides, the movement occurs along a curved surface, typically concave upwards. This mode of failure is common in cohesive soils or weak rock layers where the material moves downslope in a rotational or sliding motion. Slumps often occur in areas with steep slopes. Heavy rainfall, saturation of soil, or undercutting of the slope base trigger such slumps.
- ii. **Translational Landslides:** Translational landslides involve the movement of material along a roughly planar surface, typically parallel to the slope gradient. This mode of failure is common in cohesive or poorly consolidated soils, where a relatively coherent mass of material moves downslope. Translational landslides can occur due to factors such as slope instability, seismic activity, or erosion of the slope toe.

Bridge structure coming in the path of such slump or translational landslide subject the substructure of the bridge to immense horizontal force due to mass of sliding soil. The piers and substructure of the bridge experience shearing action. Velocity of soil influence the sliding of bridge with the soil. Unseating of the entire bridge could occur when the soil mass around the bridge foundation starts to slide.

- iii. **Rock falls and Rockslides:** Rock falls and rockslides involve the detachment and rapid downslope movement of individual rock fragments or entire rock masses. These events are common in steep rocky terrain. Weathering, freeze-thaw cycles, seismic activity, or undercutting of rock faces triggers such rock fall or rockslide. Rock falls and rockslides pose significant hazards to infrastructure and communities located below steep slopes.

- iv.** Debris Flows (Mudflows): Debris flows, also known as mudflows or lahars, are fast-moving mixtures of water, rock, soil, and other debris. These highly fluid flows can occur on steep slopes or in channels. Intense rainfall, rapid snowmelt, volcanic eruptions, or earthquakes are triggers for such debris flows. Debris flows can transport large volumes of material over considerable distances, posing significant risks to downstream areas.
- v.** Creep and Slow Movements: Creep refers to the slow, gradual downslope movement of soil or rock material over time. It is typically imperceptible daily but can cause cumulative damage to infrastructure and terrain features over the long term. Soil properties, slope angle, vegetation, and climate conditions influence Creep.
- vi.** Complex Failures (Combination of Modes): Landslides can also exhibit complex failure modes involving combinations of rotational, translational, and other movement patterns. These complex failures may occur in response to multiple triggering factors or interactions between different geological, hydrological, and environmental processes.

Understanding the modes of failure for landslides is crucial for assessing landslide hazards, mitigating risks, and implementing effective slope stabilization and landslide prevention measures. Geotechnical investigations, slope monitoring, and risk mapping are essential tools for identifying potential landslide-prone areas and developing strategies to enhance resilience and reduce vulnerability to landslide hazards. Bridge failure is predominantly due to shearing of the substructure, toppling of the superstructure, rapture of deck due to falling debris and total movement/ shifting of the bridge.

Bridges design do not account such forces. The protection measures in the surrounding areas are the only precautionary steps that the design can incorporate.

E) ANALYSIS FOR EARTHQUAKE

To be able to estimate the response of the deteriorated bridge to the occurrence of natural hazard, critically various scenarios will need analysis. The combination can run into thousand possibilities. To simplify the analysis certain assumptions are required. These assumptions relate to the type of bridge, the geometry of the bridge, the severity of natural hazard, and the orientation of the bridge with respect to the natural hazard. Typical analysis for piers subjected to earthquake occurrence illustrated herein under.

To analyze bridges subjected to earthquake we assume some geometry for each of the bridge element. The failure of bridge component is heavily dependent on the status of the component. These observations regarding the status recorded annually for each bridge component during the bridge inspection procedure. Data so collected pertains to the structural rating for deck, superstructure, substructure and foundation. It also has data relating to the deterioration symptoms, which in turn linked to the cause of deterioration. The location details of the bridge play a significant role in the whole cause identification. Environmental parameters are heavily depend on the location. Deterioration process at times depend on environmental

conditions. Global Analytics for Bridge Management [GABM] captures the entire data essential to define the deterioration process. The various modules of GABM allow the bridge inspection team to input the required data. Rating for all four components captured under Bridge Structural Rating number. Symptoms modules capture details of symptoms in various components. Linking the symptoms to cause matrix is feasible in GABM using the Artificial Intelligence driven algorithm. The user based on observations during bridge inspection can also prepare cause matrix. The intricate details of bridge locations and the impact of the location on the bridge deterioration process captured under the Location module of GABM.

All the above information integrated with details in the Risk Module related to the geographical / regional risk parameters for a particular hazard. Geographical parameters govern the risk index of the region for a particular hazard. Globally this data is documented and available with most local authorities. Using this data within the risk module of the GABM, the individual Bridge Vulnerability Index [BVI] defined for a particular hazard. BVI then enables evaluation of Bridge Risk Index for that hazard. All this analysis is feasible in Global Analytics for Risk and Resilience Management [GARM].

For earthquake, the following failure scenarios evaluated.

- i. Pier failure due to shear.
- ii. Superstructure unseating but not toppling.
- iii. Superstructure unseating and resulting in toppling due to poor support condition or failure of support after unseating.
- iv. Superstructure collapsing due to edge crushing.

The horizontal force acting due to Earthquake evaluated. This force depends on the scale of severity. The force acting on various bridge components determine when compared to the component's capacity determines the failure scenario. Deterioration process and stage determines the properties of concrete and reinforcement considered in capacity evaluation.

For Flooding, the following failure scenarios evaluated:

- i. Upstream bank erosion.
- ii. Loss of bearing arising from dislodgement or unseating of bearing.
- iii. Displacement of superstructure horizontally or due to vertical lifting and dislodgement post receding of flood waters.
- iv. Overloading due to debris on deck or superstructure.

For Landslides the failure scenario evaluated include impact of landslide flow on the shearing of substructure and the impact of falling debris on the deck for a very high level.

Flash flooding caused by cyclones creates failure modes under cyclone.

Presenting the simplified overview of the approach:

Data essentially required for the algorithm consists the following:-

- i.) Geometrical data of the bridge. The span arrangement, type of piers, shape of pier, dimensions of pier's height, diameter or width and depth, details of reinforcements, number of piers, girder in one span/

- support. Girder shape, dimensions, details of reinforcements. Details of deck geometry, unsupported height of pier.
- ii.) Geographical data relating to classification of zone in which the bridge is located. Previous historical occurrence of natural hazards, their severity and periodicity.
 - iii.) Data from Global Analytics of Bridge Management [GABM] relating to the Bridge Structural Ratings [BSRN], Ratings for natural hazards, details of symptoms and details regarding the symptoms location and severity. Loading on bridge deck in terms of dead load and live load (UDL)
 - iv.) Data relating to natural hazard, values relating to the measurement of intensity (for flood waters: values captured from historical data relating velocity of water, height of floods recorded, sedimentation ratio, density of flood water.
 - v.) Data relating to deterioration process in bridges recorded from previous experience regarding BSRN and the impact of deterioration on concrete and reinforcement.

Based on this data, the algorithm then evaluates for failure scenario based on occurrence of natural hazard and its recorded data relating to severity, extend. Actual occurrence values can determine the fate of the bridge component for each of the possible failure mechanisms stated hereinabove.

Analysis possible to evaluate the probability of the bridge failure under different hazard severity to identify the severity that can cause the bridge to collapse. This analysis is very useful for the establishing the boundaries parameters for resilience of the given bridge under the known status of deterioration.

From each failure mode analysis for various failure modes of earthquake, flooding, cyclone and landslide, emerge the probability of the bridge surviving or failing. Even one instance of bridge failure, tantamount to a result that point out the high probability of bridge failure. In case of only one type of natural hazard occurrence, analysis for that hazard conducted taking into account the level of severity of the natural hazard as recorded. Rescue and relief agencies can use the result of this analysis to decide which route to follow and reach the disaster zone. This entire analysis drives the user interface of the Resilience Module of GARM.

F) OBSTACLES TO ENSURING RESILIENCE

Ensuring resilience, particularly in the context of bridges, involves identifying and addressing various obstacles. Overcoming these obstacles enhance the ability of the structure to bounce back from disruptive events or shocks.

Below listed are few obstacles on the journey to resilience:

- i. **Limited Resources:** Resilience in any structure or system needs proactive approach. Such proactive approach needs the community to predict the worst scenario. Avoidance of such scenario need implementing measures in a proactive manner.

- ii. **Complex Interdependencies:** Modern systems are highly interconnected and interdependent. This complexity introduces challenges in understanding how disruptions in one part of the system can propagate and affect other components. Identifying and managing these interdependencies is crucial for resilience planning but can be difficult due to the intricate nature of modern infrastructure systems.
- iii. **Uncertain Future Conditions:** Predicting future threats and hazards accurately is inherently uncertain. Climate change, technological advancements, and socio-economic shifts introduce unpredictability into resilience planning. Anticipating and preparing for a wide range of potential future scenarios requires adaptive and flexible strategies.
- iv. **Inadequate Planning and Preparedness:** Lack of comprehensive planning and preparedness can hinder resilience efforts. This includes deficiencies in risk assessments, emergency response plans, and coordination among stakeholders. Without robust planning processes in place, organizations may struggle to respond effectively to disruptions when they occur.
- v. **Technological Vulnerabilities:** Reliance on complex technologies introduces vulnerabilities that can be exploited by malicious actors or susceptible to technical failures. Cyberattacks, system breaches, and infrastructure malfunctions pose significant threats to resilience. Strengthening cybersecurity measures and enhancing technological resilience are critical components of overall resilience strategies.
- vi. **Inequality and Vulnerable Populations:** Socio-economic disparities and marginalized communities are often disproportionately affected by disruptive events. Ensuring resilience requires addressing these inequalities and vulnerabilities, as well as actively involving these communities in resilience planning and decision-making processes.
- vii. **Resistance to Change:** Resistance to change within organizations or communities can impede resilience efforts. Overcoming inertia and fostering a culture of resilience requires effective communication, stakeholder engagement, and leadership commitment.
- viii. **Short-term Thinking:** Another obstacle is short-term thinking or a focus on immediate gains over long-term resilience. Decision-makers may prioritize cost-cutting measures or quick fixes that address immediate concerns but fail to address underlying vulnerabilities or invest in sustainable resilience-building strategies.
- ix. **Political and Institutional Barriers:** Political and institutional barriers, such as bureaucratic red tape, conflicting priorities, and regulatory challenges, can impede resilience initiatives. Lack of coordination among government agencies, competing interests, and reluctance to invest in long-term solutions due to political cycles can hinder progress in building resilience.
- x. **Social and Economic Disparities:** Social and economic disparities within communities can create barriers to resilience. Vulnerable

populations, including low-income communities, minorities, and marginalized groups, often bear the brunt of disasters and face challenges accessing resources, services, and information. Addressing these disparities is essential for building equitable and inclusive resilience.

- xi. Limited Awareness and Education:** Limited awareness and education about resilience concepts, risks, and mitigation strategies can impede efforts to build resilience. Effective communication and public outreach are essential for increasing awareness, fostering community engagement, and promoting proactive resilience planning and actions.
- xii. Climate Change and Environmental Degradation:** Climate change and environmental degradation pose significant challenges to resilience. Rising temperatures, extreme weather events, sea-level rise, and other climate-related impacts exacerbate existing vulnerabilities and increase the frequency and severity of disasters. Adaptation measures and sustainable environmental management are critical for enhancing resilience in the face of these challenges.

One of the primary obstacles is the availability of limited resources, both financial and human. Along with the absence of resource, other listed obstacles create an impediment to achieve resilience. Developing and implementing resilience strategies often require significant investments in infrastructure upgrades, technology, training, and maintenance. Limited funding can constrain the ability to invest in resilience measures, leaving systems vulnerable to disruptions. Interdependency coupled with the inertia to implement change in a dynamic technology evolution scenario all make resilience a distant dream for many communities. The most vulnerable communities are the communities that undertake short-term action, which dissuades implementing objectives that results in resilience. Many times, the local communities believes and opinion prevent decision makers to undertake reforms and implement steps that can result in resilience. In other instances, the will of the decision makers is not in harmony with the steps needed to usher in resilience.

Addressing these obstacles requires a holistic and integrated approach that encompasses risk mitigation, preparedness, response, and recovery efforts. By identifying and understanding these challenges, stakeholders within the communities can develop effective strategies for enhancing resilience and reducing vulnerability to future disruptions.

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IMPACT OF RESILIENCE OF BRIDGES ON POST CALAMITY SCENARIO

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A) ABSTRACT:

The resilience of the region is the ability and swiftness of that region to bounce back to normal conditions in a cost-efficient manner. Regional resilience depends on the overall development of the region, which assist to withstand the vagaries of natural hazards. Transportation network contribute to this requirements. Bridges within the region play a crucial role in this property of the region. Connectivity ensures regional resilience.

Bridges enable connectivity and are important components of any road or railway network. Resilient bridges enable not just the provision of connectivity but also ensure the continuation of the needed connectivity. Collapse of bridge during occurrence of natural hazards would lead to loss of connectivity. Success or failure of any rescue and relief operation depends on this connectivity. The multiplicity of key routes increases the chances of success of relief operation. Timely rescue and relief results in reduction of loss of lives and restoration of normalcy in the region. Normalcy results in revival of economic activities resulting in stability in the region [1, 2, 3].

Loss that accrues to the region can be manifold due to absence of resilience. The loss is not restricted to economic growth or loss of asset due to the collapse of the asset, loss can accrue due to lost human lives, lost livelihood, loss to businesses and traders due to reduced productivity, loss arising from lost connectivity and breakage in supply chain, loss due to trauma arising due to occurrence. All these cannot be accounted in Dollar terms and hence leave a gap in estimation of loss.

B) INTRODUCTION [1, 2, 3]:

Definition of Resilience of the region is the ability and swiftness of that region to bounce back to normal conditions in a cost-efficient manner. Resilience of the region defines how a region is able to maintain the normalcy at all times including post occurrence of natural hazards. Natural hazards magnify into a calamity when there is disruption to normalcy. Loss of lives, stoppage of economic activities, and collapse of infrastructure all define Calamity. Not every occurrence of Natural hazard leads to calamity. Stronger the resilience of the region, less are the possibility of natural hazard becoming a calamity.

Regional progress is measured and heavily dependent on the establishment of stable infrastructure. Stable infrastructure is an enabler for stable and steady economic growth. Economic growth can translate into higher income for the community and good employment opportunities for the residents of the region. Infrastructure are facilitators for this growth. Transport networks constitute an important component of Infrastructure.

Bridges enable connectivity and are important components of any road or railway network. Bridges within the region play a crucial role in maintaining the resilience of the region. Resilient bridges enable not just the provision of connectivity but also ensure the continuation of the needed connectivity. Connectivity ensures Regional resilience. The multiplicity of key routes increases the promptness of post-disaster rescue and relief operations. This result in an exponential decline in time required for response mobilisation.

C) IMPACT OF RESILIENCE OF BRIDGES [4, 5, 7, 8, 10];

New infrastructure / bridge assets designed and planned, built and maintained to account for the occurrence of any natural hazard of the highest severity during the life cycle of the infrastructure, result in resilience. Aging and deteriorated bridge infrastructure will undergo rehabilitation and future maintenance designed to render bridges safe and stable for the forces of natural hazards of high severity. Certain measures like dyke walls, increased height of dam will provide the much-needed protection against the changes in water level during floods or cyclones. Even natural protections systems are encouraged like mangroves, wetlands. Rules and codes preventing construction of housing in disaster prone areas also contributes to resilience in the region.

Resilience of bridges is not accidental. Research, Efforts and Sustained planning and maintenance results in resilience of bridges. The impact of resilience in bridges ensures resilience of the transport network. Post occurrence of natural hazard in the region, the resilience of bridges and the resulting resilient transport network yields direct benefits to the immediately mobilized rescue and relief work in the affected zone. The resilience also contributes indirectly to the region. The indirect benefits arise from the faster revival of economy, lesser loss of human lives and other similar benefits.

• **DIRECT IMPACT**

1. **Restoration of normalcy:** Rapid response to the affected people and area is key to survival and restoration of normalcy in the affected zone. Essentially, linked to the sustenance of economic activities and growth in the region's productivity, results in revival of normalcy. Success of rescue operations depends on the lives saved. The arrival of rescue teams within few hours of the occurrence of the hazard enables the teams to offer relief and rescue the most needed people. Golden hour is the term used to define the time-period when people affected need the rescue and relief the most. Lives are saved when the rescue teams reaches the hazard zone within the golden hour. Connectivity directly affects the arrival of the rescue team in the zone of influence within the golden hour. Availability of seamless travel route is critical for the team. Multiplicity of routes from the zone of mobilization to the zone affected enable the rescue and relief agency to choose the most suitable route. Multiplicity also offers availability of an alternative route should any hurdle obstruct usage of one route.
2. **Regional economic growth:** Under normal circumstances, the same network of roads increases the productivity of industrial and agricultural activities. Road networks act as catalytic agents for economic activities during

normal times. The multiplicity of routes with resilient bridges ensures to increase in the efficiency and preparedness of the region towards rescue and relief operations.

Incorporation of resilience in bridges is never a short-term investment. All out, efforts by all active stakeholders in the region ensure total resilience of the region. Such resilience enables speedy Disaster recovery preparedness and reduces the risk to the region. The benefits of investing in resilient bridges and infrastructure go beyond the primary objective of disaster recovery. Such investments provide long-term benefits to the region by fortifying the region to withstand future calamities. By prioritizing and having a mandatory policy at the planning stage to incorporate resilience in basic design philosophy, the region invests their finances, efforts and time to fortify itself to ensure rapid and effective response in times of crisis. Such efforts and planning has other benefits like long-term increments in economic growth of the region and employment opportunities for the community. It empowers businesses and trade.

3. **Disaster recovery:** Bridges have a multiplier effect on the efficiency of disaster recovery. Bridges ensure much-needed connectivity and access to rescue operations. Bridges ensure mobility for relief activities. Relief activities require ease of mobility for personnel and medical equipment, medicine, water, relief equipment like tents, mobile sanitation centres, and other essential items. Resilient bridges ensure the safety during movements and connectivity required for sustained mobility. They ensure the restoration of normalcy. Normalcy is essentially required for sustained economic activities. Resilient bridges ensure speedy recovery progress and economic revival. Past research and UNDRR studies revealed that every single dollar investment in resilience resulted in four times the return on investment. During normal times, this investment results in increased employment and trade.

- **INDIRECT IMPACT**

Unaccounted impact of resilience, are the indirect benefits that accrue to the community due to resilient infrastructure. Generally, the estimation or evaluation of the benefits and the costs account for only those amounts that are evident and tangible. Intangible benefits and costs are difficult to evaluate and hence unaccounted in the estimates and evaluation.

1. **Regional Resilience:** Resilience of the region or country tantamount to a scenario, where the entire systems essential for disaster risk reduction are in place and efficiently geared for the next occurrence of the natural hazard. Under such circumstances, the local communities are in a high level of preparedness. The entire population is relaxed due to their faith in the systems implemented. Such a relaxed population will yield very high productivity. The region will witness sustained economic growth. Infrastructure is evolved and efficient. Economic growth results in safety and security to the population.

2. **Safety and security:** The benefits of stability, sustained overall economic growth, employment opportunity, safety and security of all essential parameters like food, fuel, energy, water, shelter. Fuel and energy security arises from stability in the region and enhanced economic growth of the region or country. This security provides impetus to economic activities resulting in growth of long-term nature. Contribution from resilience towards this growth is difficult to evaluate and hence not considered in estimation of benefits or cost. The fuel and energy security should percolate to the rural regions also for the long-term benefits to accrue.
3. **Resilient population:** Stability in the country offers another security. This is security of shelter, food and water to the population of the country. Various studies have highlighted the fact that population with these securities (shelter, food and water) are very resilient and are involved in the overall development of the region. When the stability of the region/ country is in conjunction with the social and environmental stability, not much migration occurs. The percentage of Population displaced is low and refugee seekers are non-existent. Lower percent of displaced population yields very high productivity. UNDRR in their study in 2023 recognized this disparity and focused on eliminating this disparity.

- **DISASTER PREPAREDNESS**

The existence of resilience in any infrastructure is not accidental. A lot of research is required to frame standard procedures for design and construction, which adopt environmentally friendly. In the post-disaster scenario, hazards cause havoc to the infrastructure. Many historical narratives confirm that bridge collapse is a reality. Estimates of global loss of about USD \$350 billion are lost due to natural hazards only in infrastructure damage or collapse. World Bank estimates global cost due to natural hazards is upwards of USD \$520 billion in consumption loss, human and economic loss.

United Nations reiterated these findings in the interactive discussion on the International Day for Disaster Reduction in 2018. It further recognized that Reducing Disaster Risk is the biggest challenge for development.

Researchers in various countries have also accepted that the study of past collapsed bridges signifies how and why bridges have collapsed. It has also highlighted the need to bring a new perspective in risk assessment to overcome limitations of the current methodology to determine which ageing bridges survive after a natural hazard occurrence.

In real scenario bridges, which are the key components of any network, restore speedy normalcy and act as catalysts for recovery progress by ensuring continuous commercial activities, which are critical for the revival of economies. Resilient bridges ensure protection to regions from future disasters. Many researchers have attributed the title of LIFELINE to the transportation network. The World Bank for a document published by them also adopts this.

Bridges have gained importance. Now for any network, bridges play a major role in normal activities of the region. The demographic distribution of bridges globally is aging. Aging bridges will have witnessed deterioration process. Post occurrence

of a natural hazard, many bridges are susceptible to collapse. It is critical for the bridges to be resilient so they are able to provide required connectivity.

Implementation of adequate framework is essential to enforce the concept of resilience. Such legislation would enforce proper designs and construction of resilient bridges. It would allow the additional four to five percentage of expenditures to the required resilience in bridges. Research indicates that approximately five percentage of cost increases. Also regular inspection and maintenance is essential.

D) IMPACT DUE TO INADEQUATE RESILIENCE OF BRIDGES:

In scenarios where the regional network fails to incorporate resilience into its infrastructure, particularly bridges, the consequences can be severe, leading to a state of total chaos. The effect arising from inadequacy are either direct impact or indirect impact.

- **DIRECT IMPACT**

- 1. Disruption of Transportation:** Inadequate resilience of bridges can lead to their failure during occurrence of extreme natural hazards (events such as earthquakes, floods, or hurricanes). This directly disrupts transportation networks, making it difficult for people and goods to move across regions. The collapse of bridges hampers the normal flow of traffic, affecting daily commutes and emergency response routes. Disruption of transportation leads to total collapse of all other systems that are essential for resilience. The various benefits that arise from an efficient transportation network towards safety, security, economic growth are all lost.
- 2. Loss of Lives and Injuries:** Bridge failures can result in the loss of lives and injuries. When a bridge collapses unexpectedly, vehicles and pedestrians on or around the structure come in the harm's way, leading to fatalities and casualties. The immediate impact on human life can be devastating, especially if the collapse occurs during peak traffic times. This complicates the scenario and diverts the attention of rescue and relief agencies. If the bridge collapse occurs on the route to the disaster zone, the rescue and relief operations in this bridge collapse zone delays the actual rescue operations from the actual zone of influence.
- 3. Property Damage:** Beyond the loss of lives, inadequate bridge resilience can cause significant damage to surrounding infrastructure and properties. The collapse of a bridge may damage roads, buildings, and utilities, exacerbating the overall impact on the community.
- 4. Economic Disruption:** Transportation disruptions and damages to infrastructure can lead to economic losses for businesses and individuals. Bridges ensure connectivity within the transportation network. A collapse results in loss of seamless connectivity. Alternate routes are available within the network but are time consuming and cost inefficient. Connectivity results in ease of movement for employees and goods. This is lost. The inability to

transport goods and services efficiently can result in financial setbacks for industries and communities, further exacerbating the economic impact.

- **INDIRECT IMPACT** [6, 7]

- 1. Delayed Rescue and Relief Operations:** The lack of resilience in bridge infrastructure hinders the timely response of emergency services. Challenging scenarios arise for emergency personnel impeding speedy rescue and relief operations as damaged bridges make it difficult to reach affected areas swiftly. Delays in assistance can escalate the severity of injuries and increase the risk of further casualties. Every hour of delayed rescue and relief inputs results in more fatalities and a collapse of the community's faith in the system. The community in the long term loses their faith, resulting in delayed resilient community establishment.
- 2. Isolation of Communities:** Inadequate resilience in bridges can isolate communities, cutting them off from essential services, supplies, and support systems. This can lead to a breakdown in community resilience as people struggle to cope without access to medical facilities, food, and other necessities.
- 3. Long-Term Economic Consequences:** The indirect impact of inadequate bridge resilience extends to the long-term economic consequences. Communities that face prolonged disruptions in transportation and infrastructure may experience a decline in property values, loss of businesses, and a slow recovery from the overall economic downturn. Delay caused due to time lost in reconstruction of the bridge, results in shifting of business to locations that offer ease of movement. Such shift of business has cascading effects on employment, trade and economic growth of the region.
- 4. Psychological and Social Impacts:** Witnessing the collapse of critical infrastructure, such as bridges, can have lasting psychological effects on communities. Fear, anxiety, and trauma may persist among residents for a long time even after restoration of the connectivity, affecting the social fabric and mental well-being of the affected population. Scepticism in the regional population is a collapse of regional resilience.

The impact of inadequate resilience in bridge infrastructure is multifaceted, affecting not only the immediate safety and well-being of individuals but also the long-term stability and prosperity of communities and regions. Addressing these vulnerabilities through improved resilience measures is crucial for ensuring the overall safety and sustainability of infrastructure networks.

E) DISASTER PREPAREDNESS: HOW CRITICAL IT IS TO SAVE LIVES [9,

11, 12];

The comparison of similar hazard occurrences brings out this fact more acutely. Two similar earthquakes in two different countries bring out the reality of the importance of preparedness for any disaster. Turkey experienced a 7.8-magnitude earthquake in February 2023, while Japan experienced a 7.6-magnitude quake also in February 2023. In Turkey the fatalities were about 59,000 while in Japan the death toll was about 50. The severity was nearly the same. The energy released

by the earthquake in Turkey must have been higher than that released by the earthquake in Japan. The location played a decisive role. Densely populated Turkey suffered large number of fatalities.



(Photo credit Boston University and Kashmir Life news)

Influence of regional social and economic instability, damaged infrastructure, and international relations affect Rescue operations. Social instability results in fear in the minds of international rescue agencies to reach out to the communities in the zone of disaster. Economic instability keeps away most of the agencies. When instability is not an issue, damaged infrastructure makes the area inaccessible hampering rescue operation or causing delay in mobilization. Delay in mobilization directly affects the number of fatalities. Existence of congenial relations around the World also results in prompt help pouring the country affected. These three factors are contributory factors.

The main factor affecting the disaster response is the level of preparedness and the population density in the zone of disaster. Level of preparedness has to be holistic in nature. Proper regulatory framework is essential. Stringent adherence to the codes of construction and maintenance ensures the resilience in infrastructure. Hazards magnify to calamity when infrastructure collapses. Natural disasters are unavoidable; mitigation of the impact happens with proactive measures such as the enforcement of stringent rules and codes. The community has to adhere to the rules and codes to avoid occurrence of collapse. This adherence leads to overall development of resilient infrastructure. Population survives the disaster; response is faster and effective to enable revival of normalcy in the community affected by the hazard.

The regulatory framework alone is not sufficient. Communities need proper information dissemination and warning systems need to be in place. Untrained population's response will lead to chaos. Disciplined population results in early revival of normalcy. Training in Self-preservation techniques is essential in every community at micro level. At Macro level, the authorities and the community react in tandem to ensure a structured approach in post disaster scenario.

In contrast, survival of the asset in absence of regulation and codes for creation of assets is a chance. Post disaster, large-scale collapse of infrastructure in conjunction of collapse of houses or shelter used by the majority of the population, leaves entire communities without shelter, without food and fuel supply. This brings in insecurity to the community and individual traumatized minds. The loss is indirect and massive. Evaluation of loss due to disaster does not account for

such loss. The loss is at times long terms. The trauma can have devastating influence on an individual for years. Evaluation of lost future is not accounted in calculations. Lost career and missed out opportunity are all around. Similarly, children loose valuable days. Their focus is on the struggle to survive rather than on studies and education. Repeat exposure to disaster under same circumstances, results in spiralling impact. Generations lose their bearings and results in missed out opportunities. UNDRR aptly seeks to stop this Spiral.

The importance of critical bridges and the entire transport infrastructure highlights, with their vulnerabilities to diverse hazards. Emphasis on the need for resilience quantification comes to the front. Significance of assessing bridge and network vulnerabilities, prioritizing restoration, and the role of resourcefulness in resilience necessitates speedy restoration. Security and safety (with respect to shelter, food, fuel, employment, economic growth) brought by resilient transportation is lost. The recent events in Europe during flooding highlights this scenario ^[11].

F) OECD MODELLING AND CLIMATE-RESILIENT INFRASTRUCTURE^[10]:

Major floods devastated Paris recently. Successive floods occurred in 2016, 2018 and again in 2021. Organization for Economic Cooperation and Development (OECD) initiated a policy paper ^[10] for action initiation to avoid the recurrence of damage due to flooding. Called the OECD modelling and climate resilient infrastructure, this model deals to ensure resilience. The model of the potential impacts of a major flood in Paris evaluated that Infrastructure would bear 30% to 55% of the direct flood damages, while business would suffer loss to the tune of 35% to 85% caused by disruption to the transportation and electricity supply. Therefore, the impact on business would result in an indirect impact and not by the flood itself. The planning document also stipulated that expenditure on ensuring resilience would result in reduction of direct losses and the indirect costs of disruption. Flexible, adaptive approaches to infrastructure reduce the costs of building climate resilience given uncertainty about the future.



(Photo credit CBS news)

Climate model projections are a significant source of uncertainty, particularly on a regional or local scale, but other factors (such as socioeconomic changes) are also relevant for climate resilience. Decisions about infrastructure should consider relevant uncertainties to ensure resilience across a range of potential future scenarios

Floods reoccurred in 2023 due to Storm Oscar and Storm Gerrit. This affected not just France but many other European countries. Cancellation of trains resulted in United Kingdom. Trains cancellation between main land Europe and UK occurred. This stranded passengers on both side of English Channel. Germany witnessed flooding due to wild weather. North Europe had severe weather warning for days.

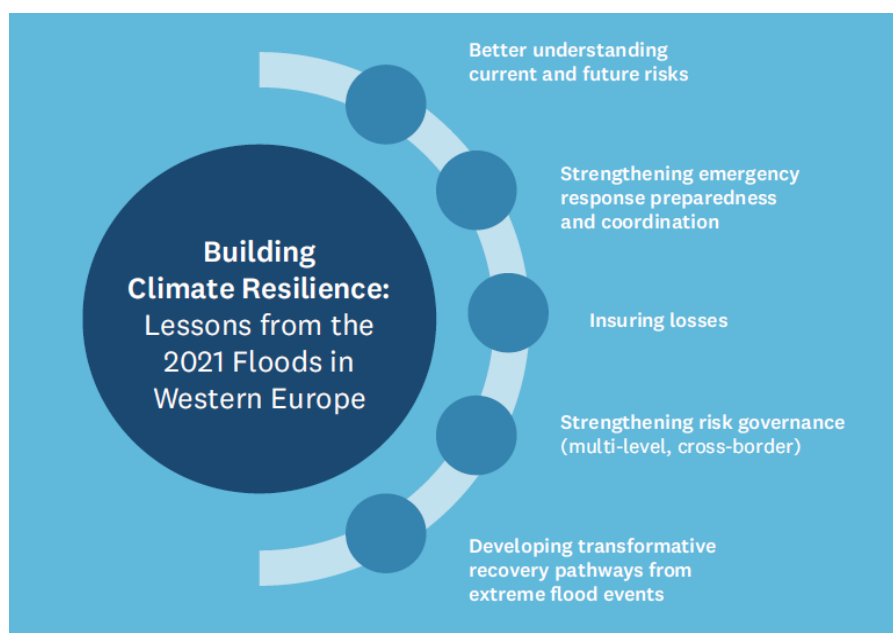
Tools discussed in OECD report were multiple aimed to encourage investment to secure resilience. The need to shift development away from high-risk areas was the key. Outlined was the need to include strategic environmental impact assessment prior to start of major infrastructure project.

G) EUROPEAN FLOOD RESILIENCE AND DISASTERS^[11, 13, 14]:

Many countries suffered from flooding in Europe during the past few years (2016, 2018, 2021, and 2023). Entire Europe has accepted the directive to ensure reduction of risk where hazards are severe or significant. Different Countries have to multiple risk assessment and management models. Key outlined directive include shifting the development away from risk prone areas. This will need changes to happen over a period. Climate changes plays havoc with the planning process. The shift in flooding area over years makes it difficult to identify which area is safe from the risk. In many countries, prevention is the main stay of the risk reduction plan. In few countries, focus is on disaster response and recovery.

UNDRR outlined a five points program. This was after the European floods of 2021. UNDRR wants the countries to understand the present and future risk better. Based on this understanding, the countries should strengthen the emergency response preparedness and coordination. Further Insurance of loss due to natural hazards to the best possible extent be undertaken. Europe is a small continent. Natural hazard occurrences do not limit to one country. This makes it essential for cross border coordination. Multi-level strengthening of risk governance is essential.

Decisions states that the built environment should become less vulnerable to extreme weather conditions and potential hazard related damage.



H) **FRAMEWORK FOR STRENGTHENING PREPAREDNESS** [2, 3, 4]:

The Sendai Framework for Disaster Risk Reduction established in 2015 (Sendai Framework) provides with seven point with concrete actions to protect development gains from the risk of disaster. The seven global targets outlined include substantial reduction of global disaster risk and mortality, number of affected people globally, economic loss, disaster damage to critical infrastructure and disruption to physical, social, cultural and environmental assets of people, communities, businesses and countries. It outlines increasing the number of countries with national and local disaster risk reduction strategies, to enhance international cooperation to developing countries, ensure global availability of and access to multi-hazard early warning system. Four priorities outlined need an understanding of disaster risk, strengthening disaster risk governance to manage disaster risk, investing in disaster risk reduction for resilience, enhancing disaster preparedness for effective response, and to “Built Back Better” in recovery, rehabilitation and reconstruction. UNDRR recommends gearing framework essential for preparedness to ensure disaster risk reduction. Consolidate existing framework.

Many organizations and research bodies devoted their research efforts to consolidate the above aim and objectives. The research resulted in methodologies proposed to achieve resilience. Three critical areas of impact outlined included Social impact, Environmental impact and Economic impact.

1. Social Impacts: The analysis of social impacts focuses on strengthening the resilience of vital road structures, particularly the weakest part in the most rural area. Identify vulnerabilities, highlighting areas for targeted infrastructure improvements. Involvement of local communities in the task brings insight. This lays the groundwork for strategic enhancements in design and maintenance policy and implementation, ultimately bolstering the overall resilience of crucial transportation network.

- **Safety Concerns:** The analysis of social impacts emphasizes safety concerns, highlighting the vulnerability of infrastructure, particularly in regions prone to frequent hazard occurrences. The potential threat to public safety due to failures underscores the urgency of addressing vulnerabilities in critical infrastructure. The analysis stresses the need to safeguard communities and maintain reliable lifeline structures to prevent disruptions in emergency responses and ensure the well-being of residents during natural hazard events.
- **Connectivity Disruption:** The analysis of social impact of event occurrences centres on connectivity disruption due to failures, affecting economic activities and cultural interactions. Beyond physical connectivity links, transportation infrastructure serve as critical lifelines, supporting communities and their compromise during events hampers daily life and emergency responses. Ensuring resilience of bridges is crucial for maintaining the flow of people, goods, and services, highlighting the pivotal role in societal well-being during natural disasters.

2. Environmental Impacts: The analysis of environmental impact focuses on developing design guide with a comprehensive structural model, anticipating failure scenarios and enhancing structural resilience during peak events. It contributes to sustainable infrastructure development by optimizing designs for extreme conditions, thereby reducing environmental consequences associated with natural hazards.

- **Damage Costs:** The study highlights the significant environmental impacts of natural hazards, with a focus on damage costs. It emphasizes the interconnected consequences, revealing that the insured costs associated with natural hazard events extend beyond financial losses to encompass broader environmental tolls. The destruction of infrastructure, especially bridges, leads to the release of hazardous materials, ecosystem disruption, and contamination. The economic burden of reconstruction efforts and environmental rehabilitation underscores the importance of recognizing and comprehending these impacts for informed decision-making and resilient infrastructure planning.

3. Economic Impacts: The analysis of economic impact assessment is a thorough evaluation that focuses on prioritizing transportation infrastructure like a bridge structures by considering the potential consequences of closure. It takes into account a range of factors, including delay costs incurred by emergency services, road-surface wear costs, and freight delay costs. To achieve a comprehensive understanding, the study introduces detailed costing models that encompass various elements such as detour routes, vehicle operating costs, accident costs, local air pollution costs, greenhouse gas emission costs, road surface wear costs, as well as costs associated with delays for the police, firefighting, and ambulance services. The ultimate goal of this comprehensive economic analysis is to establish a robust framework for conducting cost-benefit analyses in the prioritization of transportation network including bridges. This designed framework will be instrumental in facilitating funding applications and building business cases for public projects, ensuring that economic considerations play a pivotal role in the decision-making process related to critical transportation / bridge infrastructure.

- **Infrastructure Costs:** The Economic Impacts section emphasizes the significant financial repercussions of natural hazard events on infrastructure, stressing the potential for catastrophic economic losses. It underscores the broader economic implications beyond immediate repair costs, including impacts on the overall infrastructure network and regional economic well-being. The narrative highlights the urgency of addressing seismic vulnerabilities through resilient design and retrofitting to prevent prolonged reconstruction timelines and mitigate economic setbacks caused by disruptions in transportation, trade, and emergency response services.
- **Research Importance:** In light of economic impacts, such similar research stresses the urgency of investigating the natural hazard vulnerability of vital transportation infrastructure like bridges. It highlights the potential for substantial economic losses due to insufficient hazard resilience, encompassing infrastructure damage, transportation network disruption, and broader societal consequences. Advocating for proactive

research, it aims to bolster the resilience of critical transportation network including bridges, emphasizing the long-term benefits of investing in resilient infrastructure for sustained regional stability and economic robustness.

Results and Recommendations brought out by previous research indicate the need to prioritise reconstruction abiding the environmental and economic assessment principles. Ensure to explore alternate construction methods to speed up restoration. The delay or loss of connectivity results in social and economic impacts to the region serviced by the bridge. Ideally, it is best to offer alternate arrangement to keep the connectivity available.

I) The need for Resilient Bridge infrastructure

The need for resilience in bridge infrastructure is paramount. In the past decade, frequency and severity of natural hazards has increased. This has resulted in the need to provide rescue and relief promptly to the most needed communities. The increase in severity of the natural hazard has resulted in an undefined strain on the transportation networks. Bridges experience the worst of the onslaught. Many bridges have collapsed. The loss of connectivity results delay in rescue and relief emergency operations and delayed recovery of the community.

Resilient bridge infrastructure ensures that essential continued connectivity and transportation routes remain intact. Intact transportation network ensures continued movement of goods and services, essential for rescue and relief operations in the short-term and in the long-term; it facilitates continued commercial activities, trade, commerce and economic activities. All this enables prompt rescue and relief operations and recovery post occurrence of the natural hazards. The speed with which the region rebounds to normalcy is critical to avoid massive regional economic loss. Reduction in fatalities and economic loss is critical in Disaster Risk Reduction. This prevents the hazards from becoming a calamity.

Existence of resilient bridge reduces the need for exploring multiple route for the rescue and relief mobilization. Integration of technologies today make it possible to identify the least congestion route. Speedy recovery of the entire community and region is feasible due continued connectivity offered by resilient bridges. The speed of recovery post occurrence of the natural hazards also aids increased trust of the population of the region on the infrastructure. Such high trust is critical for the establishment of resilient region. Investment on establishing resilient bridges goes beyond the short-term benefits it offers for speed mobilization of rescue and relief operation to the long-term benefits, which results in enhanced resilient economy and resilient region.

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ESTABLISHING RESILIENT BRIDGE: SHORT AND LONG-TERM OBJECTIVES

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A. Introduction

Resilient bridges are indispensable components of transportation networks, instilling confidence in users and ensuring seamless connectivity. The dependency of the entire network on bridges underscores their criticality; any distress or failure in a single bridge can lead to the loss of connectivity across the entire network. Thus, the resilience of bridges directly correlates with the resilience of the network itself.

In the short term, the focus on bridge resilience primarily revolves around maintaining connectivity, especially in the aftermath of natural disasters. Transportation networks must swiftly provide access to the worst affected regions, necessitating multiple routes for redundancy and robustness. These routes are vital for the transportation of essential goods and services, including rescue and relief operations crucial for saving lives. Immediate actions post-disaster prioritize preserving structural integrity and enhancing emergency preparedness through rigorous assessment, maintenance, vigilant monitoring, and prompt repairs.

On the other hand, the long-term objectives of bridge resilience extend to fostering regional stability and economic growth. A stable and reliable transportation network is fundamental to economic development, facilitating various activities such as security, employment, trade, commerce, tourism, and cultural exchanges. Resilient bridges contribute significantly to the resilience of the entire network, echoing the sentiment expressed by former American President John F. Kennedy that "American roads are good not because America is rich, but America is rich because American roads are good."

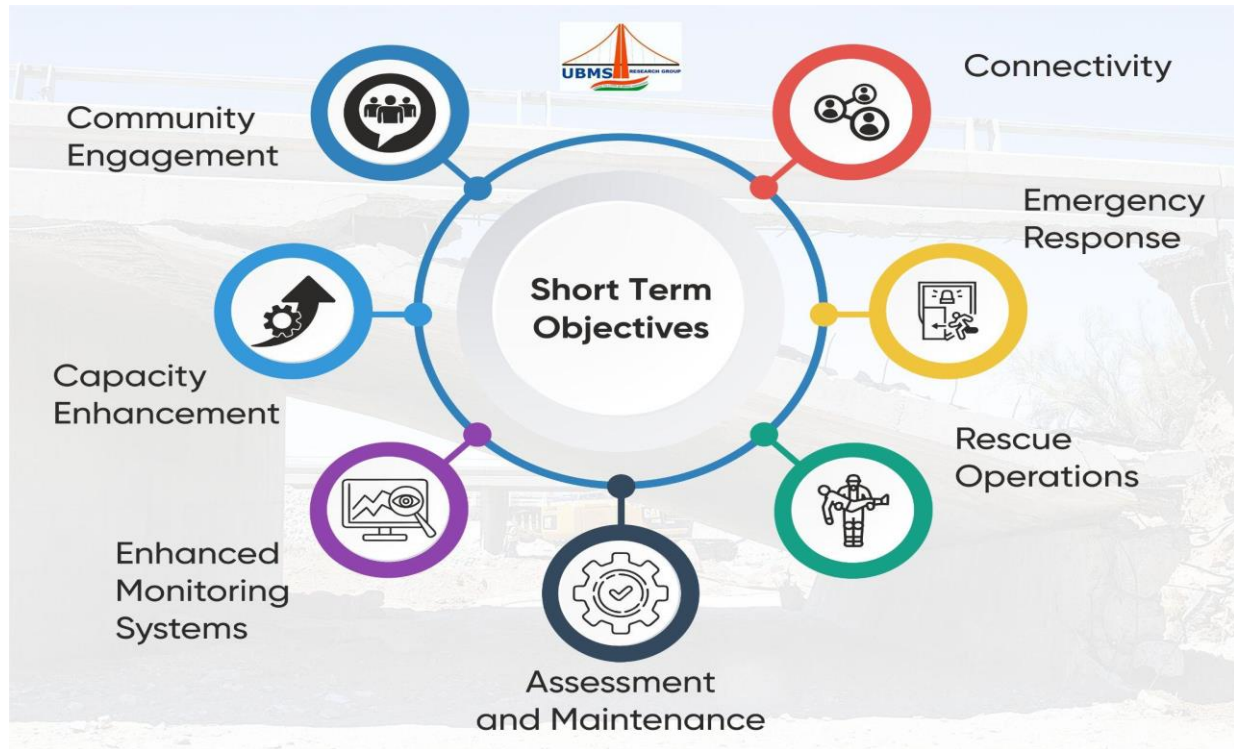
Resilient design principles for bridges encompass material selection, modular construction, redundancy, and robustness. Climate adaptation strategies play a crucial role in assessing and addressing the impacts of climate change, integrating sustainable practices to minimize environmental footprints.

Building resilient bridges transcends mere infrastructure development; it entails creating structures capable of withstanding diverse challenges and uncertainties. These structures play a pivotal role in ensuring uninterrupted connectivity, commerce, and societal well-being, especially in the face of escalating challenges posed by climate change, extreme weather events, and aging infrastructure. As urbanization accelerates and transportation demands rise, the resilience of critical infrastructure, particularly bridges, becomes paramount.

This introduction outlines both short and long-term objectives guiding the establishment of resilient bridges, emphasizing their significance in fostering sustainable and adaptable infrastructure. It underscores the necessity for bridges capable of enduring extreme conditions and adapting to unforeseen challenges,

incorporating sustainable practices and technological advancements to ensure minimal disruptions and maximize economic efficiency. Through innovative designs, materials, and construction methods, the construction and maintenance of resilient bridges pave the way for a safer, more robust transportation network, poised to meet the demands of future generations.

B. Short term objectives:



Short-term objectives of bridge resilience primarily focus on immediate actions and priorities that arise in the aftermath of natural disasters, emergencies, or unexpected events. These objectives are crucial for ensuring the continuity of essential services, facilitating emergency response efforts, and safeguarding lives and property. Let us delve into each of the short-term objectives:

i. Connectivity:

- **Immediate Restoration:** One of the primary short-term objectives is to restore connectivity swiftly. Ensuring operationalisation of roads and bridges is critical following a natural disaster or any event that disrupts transportation networks. This facilitates the movement of emergency responders, supplies, and provides safe passage to affected individuals. Bridges provide the much-needed connectivity to the transportation infrastructure.

- **Alternative Routes:** Alternate routes to reach affected zone define the robustness of the transportation network. Identification of all such routes enable one to bypass damaged or unusable bridges. If alternate routes are missing, essentially they are established. Such routes provide connectivity while repairs are being made to the affected bridges, ensuring that communities remain accessible and that critical services such as healthcare and emergency response can reach those in need. Alternate route ensure multiple routes to reach the affected zone. This accords dedicated path to each emergency service agency. Example one route for medical service providers. Second route for safe passage

to affected persons, third for relief and essential goods movement. All such routes ensure uninterrupted connectivity.

- **Temporary Solutions:** In some cases, implementation of temporary solutions such as emergency repairs, temporary bridges, or ferry services essentially restore connectivity on a short-term basis until permanent repairs or replacements completed. Maintaining inventory required for temporary solutions ensures prompt solutions. In the absence of alternate route or multiple routes, availability and maintenance of inventory is critical. Every route and region have specific conditions that do not allow all types of temporary solutions. Usage and application of correct solution precedes detailed study and feasibility evaluation of all applicable temporary solutions.

ii. **Emergency Response:**

- **Access for Emergency Vehicles:** Short-term objectives include ensuring that emergency response vehicles such as ambulances, fire trucks, and police cars can access affected areas without hindrance. To be able to achieve this short-term objective, it is critical to ensure that minimum one route is in a perfect resilient condition with all bridges on this route maintained and repaired. This involves prioritizing the repair of bridges on this route. This will provide access to emergency vehicles in a post occurrence scenario.

- **Coordination:** Effective coordination among emergency response agencies, government authorities, and other stakeholders is essential in the short term. Coordination needs logistics support, which in turn requires the transportation network is functional. Clear communication channels are the prerequisite followed by an efficient logistics. This ensures streamlined emergency response efforts resulting in maximized effectiveness and efficiency.

- **Resource Allocation:** Efficient transportation network comprises of multiplicity of routes coupled with resilience bridges. Such a network ensures fulfilment of a major short-term objective of rapid allocation and deployment of resources such as personnel, equipment, and supplies to affected areas or the zone of criticality. This ensures deliverance of emergency services promptly and efficiently to the most needed area, community and people.

iii. **Rescue Operations:**

- **Search and Rescue:** The main objective of any network and bridges on the network is to ensure seamless deliverance of rescue operation. This includes conducting search and rescue operations to locate and evacuate trapped or injured individuals because of the disaster. Existence of minimum one route, which is functional, ensures this efficient and effective search and rescue operations. This often requires specialized teams and equipment to navigate hazardous conditions and inaccessible areas.

- **Medical Assistance:** Post occurrence of the natural hazard, search and rescue operation is undertaken. Such operations defines the need for medical assistance. Providing medical assistance to survivors then assumes criticality. This may involve setting up field hospitals or medical treatment centres near affected areas to provide emergency care to the injured. All such efforts need logistics. Sound efficient and effective transportation network with resilient bridges enable this logistics.

- **Evacuation:** Few or many people in the community will need evacuation to safer place or to place where critical medical assistance is possible. Safe, efficient and

effective logistics ensure coordinated safe evacuation of residents from areas that are at risk of further harm, such as flood-prone areas or locations threatened by landslides. Required essentially, identification of evacuation routes and transportation arrangements to ensure the timely and orderly evacuation of people from danger zones.

iv. Assessment and Maintenance

- Regular inspections and maintenance serve as the cornerstone of preserving bridge integrity.
- In the short term, these activities focused on identifying and rectifying immediate issues that could compromise the structural soundness of the bridge.
- This includes vigilant monitoring for signs of structural deterioration, corrosion, and other forms of damage that could potentially escalate if left unaddressed. Immediate repairs prioritized to prevent further degradation and uphold the safety of bridge users.

v. Enhanced Monitoring Systems

- The deployment of advanced monitoring systems constitutes another critical short-term objective. Enhanced monitoring systems for the bridges is critical to the success of establishing resilience in bridges.
- These systems leverage cutting-edge technologies to enable real-time assessment of the structural health of the bridge.
- By regular monitoring using sensors capable of measuring parameters such as stress, strain, vibration, and environmental conditions, bridge operators can proactively intervene to prevent catastrophic failures.
- Early detection of anomalies allows for timely intervention, thereby safeguarding the integrity of the bridge and reducing the risk of potential accidents or disruptions.

vi. Capacity Enhancement

- In the short term, enhancing bridge capacity involves evaluating traffic patterns and demand to implement immediate measures for optimization.
- This may entail temporary traffic management strategies such as lane closures or weight restrictions to alleviate overload conditions and ensure the continued functionality of the bridge.
- By effectively managing traffic flow and distribution, short-term capacity enhancement measures help mitigate congestion and minimize the risk of structural overstress until solutions that are more permanent implemented.

vii. Community Engagement

- Engagement with local communities and stakeholders is integral to fostering resilience and promoting safety awareness.
 - In the short term, efforts focused on raising awareness about bridge resilience and soliciting feedback on potential vulnerabilities from those directly impacted by bridge infrastructure.
 - Educational initiatives aimed at informing the public about safety measures, evacuation routes, and emergency response procedures serve to empower communities and enhance their ability to effectively respond to crises.
- Short-term objectives in bridge resilience focus on restoring connectivity, facilitating emergency response efforts, and conducting rescue operations in the

immediate aftermath of a disaster or emergency. These objectives are essential for minimizing the impact of the event, saving lives, and laying the groundwork for the longer-term recovery and rebuilding process.

C. Long-term objectives:



Long-term objectives in the context of bridge resilience encompass broader goals aimed at ensuring the sustained functionality, adaptability, and socio-economic well-being of communities over an extended period. These objectives focus on enhancing the overall resilience of the transportation network, fostering economic growth, improving the reliability and robustness of infrastructure, and promoting the safety and health of communities.

i. Resilient Network:

- **Infrastructure Adaptation:** Long-term objectives include implementing measures to adapt bridge infrastructure, to changing environmental conditions and emerging risks such as climate change, changing frequency and severity of natural hazards. This involves incorporating resilience considerations into the planning, design, construction, and maintenance of bridges to enhance their ability to withstand future hazards. It calls for proactive approach to ensure resilience in old existing bridges. Budgeting for this activity and implementing, the same will ensure sustained resilience of old distressed bridges.

- **Risk Reduction:** Strategies for long-term resilience aim to reduce the vulnerability of the transportation network to various threats, including natural disasters, extreme weather events, and other disruptions. This may involve investing in hazard mitigation measures, such as improved drainage systems, flood barriers, or slope stabilization techniques, to minimize the impact of disasters on bridges and infrastructure. There is a vast opportunity for natural measures to achieve resilience in transportation infrastructure including bridges.

Often neglected aspect including upstream and downstream channel / river basin augmentation will restore the needed robustness against flooding.

- **Continual Improvement:** Long-term objectives also include fostering a culture of continual improvement and learning within the transportation agencies and engineering communities. This involves monitoring performance, conducting risk assessments, and implementing lessons learned from past events to enhance the resilience of the network over time. The need to enhance bridge management techniques and systems to incorporate the risk assessment arises from this need to ensure continual improvement of existing systems of management.

ii. **Economic Growth:**

- **Enhanced Connectivity:** Long-term objectives seek to promote economic growth by enhancing connectivity and accessibility within and between communities. Resilient bridges play a crucial role in facilitating the movement of goods, services, and people, thereby supporting economic activities such as trade, commerce, tourism, and employment.

- **Infrastructure Investment:** Investing in resilient infrastructure, including bridges, contributes to long-term economic growth by increasing productivity, reducing transportation costs, and attracting investment. Resilient bridges seen as essential assets that underpin economic development and competitiveness in a globalized economy.

- **Job Creation:** The construction, maintenance, and operation of resilient bridges generate employment opportunities and stimulate economic activity in local communities. Long-term objectives may include leveraging infrastructure projects to create jobs, develop skills, and foster economic prosperity.

iii. **Reliability, Robustness, and Redundancy of Network:**

- **Enhanced Reliability:** Bridges designed, built, and maintained to meet high standards of performance and safety ensure enhancing the reliability of the transportation network. This involves implementing rigorous inspection, maintenance, and repair programs to address deterioration and prevent failures.

- **Robustness and Redundancy:** Long-term resilience strategies aim to increase the robustness and redundancy of the network by diversifying routes and modes of transportation. This includes investing in alternative transportation options, such as public transit, cycling infrastructure, and pedestrian pathways, to reduce reliance on any single bridge or road corridor.

- **Disaster Preparedness:** Long-term objectives include strengthening the network's capacity to respond to and recover from disasters by developing emergency response plans, stockpiling critical supplies, and improving coordination among stakeholders. This ensures maintenance of essential services during times of crises.

iv. **Safe and Healthy Community:**

- **Public Health and Safety:** Bridges provide connectivity, which is vital for the public health and safety. Resilient bridges provide long-term safety net to the entire community. Ensuring that bridges designed and maintained to meet stringent safety standards provides resilience. This includes measures to protect

against structural failures, accidents, and other hazards. The population in the community is at ease due to the continuous connectivity. This leads to sustained growth of the region and in turn the safety to the community.

- **Environmental Sustainability:** Considerations of environmental aspects into bridge design and construction, minimizing adverse impacts on ecosystems, air quality, and water resources. This promotes the creation of sustainable and liveable communities that are resilient to environmental change.

- **Community Engagement:** Engaging communities in the planning, design, and management of bridge infrastructure provides the long-term sustainable resilience to bridges. This fosters a sense of ownership and stewardship among residents, leading to more sustainable and resilient outcomes.

v. Lifecycle Planning

Lifecycle planning forms the cornerstone of effective bridge management. It involves developing comprehensive strategies that encompass the entire lifespan of the bridge, from initial construction to eventual replacement. Key considerations include:

- **Maintenance Strategies:** Establishing routine inspection schedules and maintenance protocols to ensure the structural integrity and operational efficiency of the bridge over time.

- **Rehabilitation Plans:** Identifying potential deterioration factors and implementing timely interventions to rehabilitate aging infrastructure and extend its lifespan.

- **Replacement Strategies:** Anticipating the end of the bridge's service life and planning for orderly replacement or major upgrades to prevent disruptions in transportation networks.

vi. Risk Assessment and Mitigation

Risk assessment is essential for identifying potential hazards and vulnerabilities that may compromise the bridge's safety and functionality. Mitigation measures aim to reduce these risks through proactive interventions such as:

- **Hazard Identification:** Conducting thorough assessments to identify natural and manmade hazards, including floods, earthquakes, corrosion, and vehicular impacts.

- **Vulnerability Analysis:** Evaluating the bridge's susceptibility to identified hazards based on structural, environmental, and operational factors.

- **Mitigation Strategies:** Implementing engineering solutions such as reinforcement, retrofitting, and diversion to mitigate risks and enhance resilience against potential threats.

vii. Incorporation of Resilient Design Principles

Resilient design principles focus on enhancing the bridge's ability to withstand and recover from adverse conditions. Key considerations include:

- **Material Selection:** Utilizing advanced materials with high strength, durability, and resistance to corrosion, fatigue, and environmental degradation.

- **Modular Construction:** Adopting modular construction techniques to facilitate rapid deployment, reduce construction time, and minimize disruption to traffic.
- **Redundancy and Robustness:** Incorporating redundant structural elements and robust design features to ensure structural integrity and functional redundancy in the event of component failure or extreme loading conditions.

viii. Climate Adaptation

Climate change poses significant challenges to bridge resilience, necessitating proactive adaptation strategies:

- **Impact Assessment:** Assessing the potential impacts of climate change, including increased frequency and intensity of extreme weather events, sea-level rise, and temperature fluctuations.
- **Adaptation Measures:** Implementing adaptation measures such as raising bridge elevations, incorporating flood-resistant designs, and improving drainage systems to mitigate climate-related risks.
- **Sustainable Practices:** Integrating sustainable design practices to minimize carbon footprint and enhance environmental resilience in the face of climate uncertainty.

ix. Research and Innovation

Investment in research and innovation is essential for advancing bridge engineering technology and resilience:

- **Collaborative Partnerships:** Establishing partnerships with academic institutions, industry stakeholders, and government agencies to foster interdisciplinary research and knowledge exchange.
- **Technological Advancements:** Exploring emerging technologies such as sensors, data analytics, and 3D printing to improve monitoring, maintenance, and performance prediction of bridges.
- **Continuous Improvement:** Promoting a culture of continuous learning and improvement through ongoing research, testing, and implementation of innovative solutions to address evolving challenges in bridge engineering.

Achieving long-term objectives in bridge engineering requires a holistic approach that integrates lifecycle planning, risk assessment, resilient design principles, climate adaptation, and research and innovation. By adopting proactive strategies and leveraging technological advancements, bridges withstand the test of time and contribute to sustainable infrastructure development for future generations.

D. Importance:

Bridge maintenance and management plays a pivotal role in ensuring the immediate safety, functionality, and resilience of bridge structures. The outlined encompass vital aspects such as assessment and maintenance, emergency preparedness, enhanced monitoring systems, capacity enhancement, and community engagement. The significance of these objectives lies in their ability to address pressing challenges promptly, thereby averting potential risks and minimizing disruptions. Assessment and maintenance of bridges on a regular basis

results in resilience in bridges. This results in preventing further structural degradation, and upholding the safety of bridge users. Pro-active approach inculcated in the philosophy of the community essentially maintains the resilience.

This results in long, sustained emergency preparedness. Community benefits from such preparedness in the long-term. This results in minimized damage to bridges during unforeseen events. The ability to respond effectively to crises, coupled with clear communication protocols and resource stockpiling, ensures the immediate safety of the bridge and its users.

Enhanced monitoring systems deployment on bridges is essential. Real time assessment of structural health and the degradation ensures avoidance of catastrophic failures. By incorporating cutting-edge technologies, these systems allow for early detection of anomalies, facilitating timely intervention. This ensures reduction of the risk of potential accidents or disruptions.

Capacity enhancement of transportation network are vital for optimizing traffic patterns and demand, ensuring the continued functionality of the bridge. Effective management of traffic flow, mitigation of congestion and minimize the risk of structural overstress, addressing immediate challenges while longer-term solutions are developed.

Engaging with local communities in the short term is integral to fostering resilience and safety awareness. Raising awareness about bridge resilience and soliciting feedback from those directly impacted by the infrastructure contributes to community empowerment, enhancing the overall response to crises.

Resilience in Bridges forms a multifaceted approach aimed at preserving structural integrity, enhancing emergency preparedness, optimizing capacity, and fostering community resilience. By prioritizing these objectives, bridge operators can effectively address immediate challenges, ensuring the immediate safety and functionality of critical infrastructure while laying the foundation for long-term sustainability and safety.

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CONCLUSIONS: NAVIGATING FROM DETERIORATED TO RESILIENT BRIDGES

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The concept of resilience in bridges is modern. Focused and sustained research needed to mature the concept. Present understanding on the need of establishing resilience emerges out of the impact of climate change and occurrence of severe natural hazards. Such occurrences are with increased frequency and severity. Solutions to establish resilience have resulted out of the need to mitigate the impact of such occurrences. Holistic Resilience of the region and community definition outlined the need to have resilient systems. Transportation network forms a critical input to sustained resilient communities. Bridges within the transportation network are important. Management systems established over last 6 decades have matured to manage the life cycle of bridges.

Bridge management systems [BMS] have always been reactive. BMS provides remedial interventions for observed or recorded symptoms. Such measures manage to eliminate the cause of distress. When the need to establish resilience came to the forefront, Bridge management teams groped around the known methodologies. Being reactive in nature, the progress was restrictive. Proactive systems were needed to identify the possibility of failure should the natural hazard occur. Bridge management identified that high percent of existing bridges in their database have deterioration. BMS focused and ensured to eliminate such identified distress. Bridge management however could not predict the behavior of such deteriorated bridges under severe natural hazards. One obstacle identified was the lack of knowledge base available to define the behavior of existing deteriorated bridges. The need arose to "**Navigate from Deteriorated bridges to Resilient bridges**".

Bridge management plays a pivotal role in ensuring the immediate safety, and continued functionality of bridge structures. It outlines vital aspects such as assessment and maintenance, emergency preparedness, enhanced monitoring systems, capacity enhancement, and continued connectivity to the community. The significance of these objectives lies in their ability to address pressing challenges promptly, thereby averting potential risks and minimizing disruptions. Assessment and maintenance of bridges on a regular basis in bridges are defined and implemented. This results in preventing further structural degradation, and upholding the safety of bridge users. All these actions helped BMS to keep the bridge inventory safe.

Resilience requires long, sustained emergency preparedness. This preparedness goes beyond the above stated BMS defined remedial intervention. Resilient bridges help the entire community. Community benefits from such preparedness in the long-term. Resilience results in minimized damage to bridges during unforeseen events. Enhanced monitoring systems deployment on bridges is essential. Real time assessment of structural health and the identification of degradation in material properties ensures avoidance of catastrophic failures. By

incorporating cutting-edge innovative technologies, these systems can offer early detection of anomalies, facilitating timely intervention. This ensures reduction of the risk of potential accidents or disruptions. Collapses in bridges have a long history. Among many causes identified for collapses, natural hazards have a fair share. Rare cases of prevention or prediction of bridge collapse exists.

Innovations in Bridge management ensured that safety and connectivity for the users. During the last few years, frequent occurrences of very high severe natural hazards; have resulted in quite a few collapsed bridges. In USA alone it is reported (Article in PreventionWeb) that during the last 2 to 3 decades, multiple hundreds of bridges failed. Any failure or collapse results in human casualties. Few reported cases of bridge failures attributing the cause to natural hazards are as follows:

DATE/ YEAR	BRIDGE	NATURAL HAZARD	COUNTRY
April 2015	Himera Viaduct	Landslide	Italy
March 2017	Pfeiffer Canyon Bridge	Rain and landslide	USA
June 2018	Rail Bridge in Budila County	Flooding	Romania
September 2018	Palu IV Bridge, Palu	Tsunami	Indonesia
November 2019	A6 Highway bridge in Savona	Heavy rain and landslide	Italy
May 2021	Metro Overpass in Mexico City	Erosion and dilapidation damage due to previous earthquake on 2017	Mexico
April 2022	Loay-Clarín Bridge	Damaged during previous year Earthquake	Philippines
September 2022	Sanibel Causeway	Hurricane Ian	Florida, USA

The above bridge collapses are not the only bridges that have collapsed due to natural hazards. Deterioration is unavoidable and so is resulting collapses. Capabilities to predict such an eventuality helps the community to be more prepared. It is critical to be able to predict and then prevent such bridge collapses to avoid human casualties, disruption to economic and commercial movements of goods, loss of connectivity and trauma due to such loss. The research study focused on the comprehensive overview of resilience in bridges from a bridge management perspective. It emphasizes the importance of resilience in bridge

design, maintenance, and management, highlighting the multi-dimensional nature of this concept. It discusses the need for quantitative measurement and assessment of bridge resilience, considering metrics such as redundancy, fragility analysis, downtime, load-carrying capacity, and adaptation capacity.

The importance of resilient bridges underscored, as bridges are not just physical structures but vital conduits of economic development, community well-being, and regional stability. Analysis of historical bridge collapses teach important lessons aimed to bring resilience in bridges. It emphasizes the importance of understanding root causes and consequences of non-rectification.

The research documentation highlights the challenges to achieving resilience in existing bridges. Challenge range from aging infrastructure to changing environmental conditions and financial constraints. The impact of climate change and natural hazards on bridge resilience discussed, highlighting the vulnerability of coastal bridges to erosion and flooding, as well as the seismic risks faced by bridges in earthquake-prone areas.

The structural considerations for defining resilience in bridges, including redundancy, load distribution, and innovative design strategies, emphasized as critical factors in enhancing a bridge's ability to withstand stressors. The use of advanced materials and smart technologies highlighted as pivotal in constructing resilient bridges, extending their lifespan, and improving their ability to withstand various challenges.

Overall, it provides valuable insights into the complex and multifaceted nature of resilience in bridges and underlines the importance of a holistic approach to bridge management and engineering, considering both current challenges and future uncertainties. Resilience in bridges is not only a matter of structural design but also a critical element in promoting overall regional economic development, ensuring community well-being, and enhancing the overall stability of regions.

The need for resilience in bridge infrastructure is paramount. In the past decade, frequency and severity of natural hazards has increased. This has resulted in the need to provide rescue and relief promptly to the most needed communities. The increase in severity of the natural hazard has resulted in an undefined strain on the transportation networks. Bridges experience the worst of the onslaught. Many bridges have collapsed. The loss of connectivity results delay in rescue and relief emergency operations and delayed recovery of the community.

Resilient bridge infrastructure ensures that essential continued connectivity and transportation routes remain intact. Efficient transportation network ensures continued movement of goods and services, essential for rescue and relief operations in the short-term and in the long-term; it facilitates continued commercial activities, trade, commerce and economic activities. All this enables prompt rescue and relief operations. Post occurrence of the natural hazards, recovery of the region and communities also happens faster. The speed with which the region rebounds to normalcy is critical to avoid massive regional economic loss. Reduction in fatalities and economic loss is critical in Disaster Risk Reduction. This prevents the hazards from becoming a calamity.

Existence of resilient bridge reduces the need for exploring multiple route for the rescue and relief mobilization. Integration of technologies today make it possible

to identify the least congestion route. Speedy recovery of the entire community and region is feasible due continued connectivity offered by resilient bridges. The speed of recovery post occurrence of the natural hazards also aids increased trust of the population of the region on the infrastructure. Such high trust is critical for the establishment of resilient region. Investment on establishing resilient bridges goes beyond the short-term benefits it offers for speed mobilization of rescue and relief operation to the long-term benefits, which results in enhanced resilient economy and resilient region.

Capacity enhancement of transportation network are vital for optimizing traffic patterns and demand, ensuring the continued functionality of the bridge. Effective management of traffic flow, mitigation of congestion and minimize the risk of structural overstress, addressing immediate challenges while longer-term solutions are developed.

Engaging with local communities in the short term is integral to fostering resilience and safety awareness. Raising awareness about bridge resilience and soliciting feedback from those directly impacted by the infrastructure contributes to community empowerment, enhancing the overall response to crises.

Resilience in Bridges forms a multifaceted approach aimed at preserving structural integrity, enhancing emergency preparedness, optimizing capacity, and fostering community resilience. By prioritizing these objectives, bridge operators can effectively address immediate challenges, ensuring the immediate safety and functionality of critical infrastructure while laying the foundation for long-term sustainability and safety.

Research aimed and focused to find a solution to the problem of identifying the degree of severity of natural hazards [earthquake, cyclone, landslide and flooding], which can cause the bridge to collapse. The degree of severity identification enables definition of required proactive approach essentially required to provide resilience in bridges. The knowledge of details of deterioration process available in Bridge Management system was the starting point.

Global Analytics for Bridge Management [GABM] application provides the data regarding the deterioration process and define the cause of distress. GABM has evolved from the Indian Bridge Management System (IBMS) to provide tailored solutions for bridge owners, incorporating validated technologies to assess conditions, predict maintenance needs, and optimize resource allocation. With modules dedicated to data management, analysis, and resource optimization, it offers a comprehensive approach to bridge management, employing technical algorithms to evaluate deterioration progression and optimize funding.

The module, which integrates the risk of natural hazards to the region with the deterioration process, helps in identifying the vulnerability of the bridge structure for a particular hazard. This Bridge vulnerability index [**BVI**] is different for various types of natural hazards, as the failure mechanism for each hazard is unique. The evaluation of BVI then enables application of various failure scenarios to the deteriorated bridge structure. Based on this analysis, the degree of severity of a particular hazard essentially required to cause the failure defined.

Bridges fail under multiple failure modes for the four hazards, which GABM restricts analysis. From the various failure modes that bridges can fail or collapse,

to enable simplification, GABM restricts the analysis to critical modes of failure for each hazard. The modes for which analysis carried out are as under:-

Earthquake:

- Pier failure due to shear.
- Superstructure unseating but not toppling.
- Superstructure unseating and resulting in toppling due to poor support condition or failure of support after unseating.
- Superstructure collapsing due to edge crushing.

Flooding:

- Upstream bank erosion.
- Loss of bearing arising from dislodgement or unseating of bearing.
- Displacement of superstructure horizontally or due to vertical lifting and dislodgement post receding of flood waters.
- Overloading due to debris on deck or superstructure.

Landslide:

- Failure due to shearing of the substructure.
- Toppling of the superstructure
- Rapture of deck due to falling debris and total movement/ shifting of the bridge.

Cyclone:

- Failure modes due to flooding are similar to those under cyclone additionally, wind gust impact is analysed.

GABM, an offline application, provides all essential analytical tools to calculate the details. This data then transferred to Global Analytics for Resilience and Risk Management [GARM]. Complementing GABM, GARM focuses on enhancing bridge resilience through advanced analytics and risk assessment methodologies. Collaborating seamlessly with GABM, it aims for dual objectives of effective bridge management and resilience enhancement, featuring modules for report generation, risk assessment, and resilience planning.

GARM is an online application available on internet. This application then processes the bridge data to generate various formats of reports that are available to the entire hierarchy for required proactive decision-making process.

The four modules of GARM are:

- **Report Generation Module:**
Post conducting bridge inspection, results evaluated in GABM are essentially required for decision-making process. Report Generation Module of GARM provides all bridge management results formatted as a Bridge report. Being online, report is available across the organization.
- **Risk Assessment Module:**
This module assesses the potential risks posed to various bridges in a network, from various hazards such as earthquakes, floods, cyclone, and landslides. It evaluates Bridge Vulnerability Index and provides Bridge Risk Index for each of the hazard.
- **Deterioration to Failure scenario Module:**
Based on the structural status of the bridge during the current year, the module evaluates the probability of failure occurring in the bridge during the occurrence

of the natural hazard. The results also can estimate the level of severity of natural hazards that can cause a failure in the bridge.

- **Bridge Resilience Module:**

This module facilitates the development of resilience strategies by identifying appropriate mitigation measures. It also prioritizes resilience actions based on the severity of risks, the criticality of infrastructure assets, and available resources. The most critical output of this module is the map-supported interface that assists the users to select the route to take to reach the zone of disaster from the present location.

GARM provides insight into the availability of a route from the base station of the Rescue team to calamity zone. Details of bridges, which show a higher probability of collapse, highlighted by Red switch. Bridges, which show high probability of surviving the event, highlighted Green. Such easy to understand user interface makes it possible for GARM assist Rescue and Relief organizations effectively. The map interface used is that of Google Map and the user department will need to install the API on their system.

GARM also provides the required remedial interventions to ensure resilience in all bridges in the network. The onus of implementing the suggested remedial interventions rests with the transportation network owners.

In essence, the integration of Global Analytics for Bridge Management (GABM) and Global Analytics for Resilience and Risk Management (GARM) marks a monumental leap forward in infrastructure management. These platforms, driven by cutting-edge analytics and methodologies, are pivotal in addressing the intricate challenges posed by natural hazards and the deteriorating conditions of bridges.

The amalgamation of GABM and GARM establishes a robust framework for proactive bridge management and resilience enhancement, empowering stakeholders to make informed decisions, allocate resources efficiently, and ensure the safety and longevity of bridge infrastructure. The duo of GABM and GARM provide valuable assistance to Rescue and Relief organizations. Assistance provided helps judge the probability of bridge failure or survival during an event of natural hazard.

Despite challenges such as resource constraints, proactive measures, and community involvement remain imperative for achieving resilience in bridge infrastructure. Resilient bridges not only ensure vital connectivity but also serve as lifelines during crises, facilitating rapid response and recovery efforts. Analysis results does not shift the onus of providing remedial interventions needed on a bridge to restore the stability or increase the resilience from the user department.

Investing in resilient bridge infrastructure yields multifaceted benefits, from saving lives to fostering economic growth and community empowerment. By prioritizing resilience in infrastructure planning and maintenance, regions can fortify themselves against future calamities, ensuring sustained growth, prosperity, and security for their inhabitants.

The pursuit of resilient bridges entails a multifaceted approach encompassing short-term restoration efforts and long-term strategic objectives. Swift restoration

of connectivity, efficient emergency response coordination, and community engagement are crucial in addressing immediate challenges, while long-term objectives focus on infrastructure adaptation, economic growth, and risk mitigation.

Ultimately, prioritizing resilience in bridge infrastructure is not just a short-term necessity but is a strategic investment in the long-term prosperity and sustainability of societies, ensuring the well-being of all stakeholders and laying the groundwork for a resilient future. Various research conducted world over have established that the cost of prevention is much less than the cost incurred post calamity.

Advent of GABM and GARM offer the various communities an opportunity to utilize the same to usher in resilience in bridges.

Further research scope exists. Research can focus on:-

- Study and analysis of various other modes of failure for the four hazards. This can include failure due to combination of various factors on multiple components simultaneously. Present analysis restrict the failure of single component due to single failure mode.
- The analysis can include many other hazards. Hazards like wild fire, volcanoes, tornadoes, high winds, snowstorms, avalanche, icebergs, and many others.
- More refinements in the existing analysis will bring in higher level of accuracy. Simplification adopted to yield results under constraints of time, financial efficiency can hamper accuracy. As technological innovation happen, cost of using technologies reduce making it financial viable. Integrating more innovative technologies will increase the cost but with time as these technologies become viable and easily available, integration will be viable.
- Use of Artificial intelligence more exhaustively will assist in refinements and exhaustive analysis. Limitation imposed presently on the applicability to only four hazards will not exists. The variability in failure mechanisms can enhance the results in realist terms.