# CRITICAL NEED TO EMBRACE AND ADAPT RESILIENCE- REFRAMING CRITICAL INFRASTRUCTURE, CONNECTIVITY, AND DISASTER GOVERNANCE

SEPTEMBER 2026


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ISBN no: **978-93-344-9832-5**
Published by UBMS Research Group
https://ubmsresearchgroup.com/blog-grid/

## ACKNOWLEDGEMENTS:

We wish to acknowledge the guidance of the global fraternity of Bridge Management and Disaster resilient infrastructure for the numerous research articles/ journals/ papers published by them and available on internet. Without that preceding research work, our efforts would not have yielded the results.

The core research team consisted of Sachidanand Joshi, and Prof. Dr. Nidhi Nagabhatla.

We owe a big thank you to each of the Members of the Board Of Advisors for their encouragement, support and Guidance, and to key researchers in UBMS Research Group namely Mayuri Tundalwar, Sreenath Menon

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Last but not the least; we owe a very big thanks to our family members and friends for their continuous support and encouragement that enabled us to dedicate our time to our research efforts.

# LET'S RETHINK RESILIENCE- CRITICAL INFRASTRUCTURE and CONNECTIVITY in DISASTER GOVERNANCE

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 ISBN no: **978-93-344-9832-5**
Published by UBMS Research Group
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## Executive message

Bridges are often treated as transport assets: structures to be designed, inspected, maintained, and replaced. This approach is no longer sufficient. Across the world, floods, storms, landslides, earthquakes, wildfires, heatwaves, and other hazards are becoming more interconnected, while aging infrastructure, urban expansion, and constrained public budgets increase vulnerability. When a bridge fails, the immediate loss is not limited to concrete, steel, or road capacity. Communities may be isolated, emergency services delayed, hospitals become harder to reach, supply chains interrupted, and local economies disrupted.

A bridge is therefore simultaneously a transport structure, a public service platform, an emergency lifeline, and a spatial-planning decision.

We argue that bridge resilience must become a central concern of disaster governance and infrastructure planning. Civil authorities and planning committees should move beyond conventional Bridge Management Systems towards Bridge Resilience Systems by integrating frameworks that connect engineering, land-use planning, emergency response, ecosystem management, climate adaptation, social equity, and long-term investment.

*The central message is simple:*

Bridges should not be assessed only by whether they function under normal conditions. They should also be evaluated according to whether they preserve, support, or rapidly restore essential connectivity during and after disruption. Such disruptions arise mostly post-occurrence of natural hazards.

This requires a shift from isolated assets to linked systems, from historical design assumptions to forward-looking risk analysis, and from repair after failure to enhancing resilience throughout the infrastructure life cycle.

*Why bridges matter in a changing risk landscape:*

Extreme events rarely remain confined to a single hazard or location. Heavy rainfall can trigger river flooding, slope failure, debris flows, road closures, power outages, and contamination of water systems. A storm surge can damage coastal roads, inundate transport hubs, and interrupt access to hospitals or evacuation routes. Earthquakes can damage bridge structures, primarily the substructure and superstructure, leading to localized collapse. Such localized collapse has the potential to cascade to total bridge collapse. Wildfires can destroy bridge approaches, weaken surrounding slopes, and sever connections between rural settlements and urban services.

These are not simply engineering problems. They are governance problems because the consequences extend across administrative boundaries, sectors, and time scales.

A bridge may be owned by one authority, maintained by another, and used by an entire regional communities that depend on services controlled by several others. Its failure can affect: emergency access and evacuation; access to hospitals, schools, and care facilities; food, fuel, and medical supply chains; commuting and regional labor markets; local business activity; communication between isolated communities; access to rescue and recovery operations; and, for a longer term, social cohesion and public confidence.

This interdependence means that the importance of a bridge is often underestimated during normal times. A structure may carry relatively modest daily traffic but become indispensable during an emergency because it provides the only connection between a settlement and essential services. The value of a bridge is therefore not captured by traffic volume alone. It also lies in its strategic position within a network and its role in maintaining access when alternative routes are unavailable.

Key aspects

**1 From asset to system thinking**

Bridges are part of a wider system within the river, coast, floodplain, or valley in which it is located; roads, railways, and pedestrian routes connected to it; drainage, embankments, retaining walls, and culverts; emergency services and evacuation plans; surrounding settlements and land uses; utility networks and digital infrastructure; and ecological processes such as sediment movement and flood storage. Such is the diversity of the conversation in systems thinking, and public institutions responsible for planning and maintenance need to embrace that thinking.

*Image credit and courtesy: https://mymodernmet.com*

System failures often occur not because a single component is inherently weak, but because interactions between components were poorly understood. For example, a bridge may remain structurally intact while its approach road is washed away. A bridge deck may survive, but debris accumulation at its supports may redirect water towards nearby homes. A route may technically remain open, but its connection to a hospital or emergency center may be cut elsewhere.

*Resilience planning must therefore assess the complete connectivity system rather than the bridge alone.*

This acknowledgment also changes the meaning of infrastructure protection. Protecting a bridge does not necessarily mean ensuring that the structure remains untouched. In some circumstances, it may be more realistic and cost-effective to design for controlled damage, rapid inspection, modular repair, or temporary replacement. The objective is not always uninterrupted performance under every possible event. It is the preservation of essential functions and the rapid restoration of access.

Noting that infrastructure is exposed to a wide range of hazards, including river and pluvial flooding, coastal flooding, earthquakes, landslides, storms, drought, wildfire, heat stress, and compound events. These hazards vary across regions, but their impacts can combine and interact in unexpected ways in cross-border regions.

In mountainous and hilly areas, intense precipitation can produce flash floods and debris flows that place exceptional pressure on bridge foundations, piers, and approaches. In river basins, altered rainfall patterns and land-use change can increase peak flows and erosion. In coastal regions, sea-level rise, storm surges, and saltwater intrusion can affect bridge materials, road approaches, and adjacent infrastructure. In cities, impermeable surfaces and constrained waterways can intensify rapid runoff and overwhelm drainage systems. In earthquake-prone zones, seismic waves can affect bridges' substructures and superstructures, road approaches, abutments, and other structures.

Various studies indicate that 55 to 70% of bridge collapses can be linked to natural hazards. [https://sciencedirect.com; International Journal of Disaster Risk Reduction, Vol 131, December 2025, 105880, Extreme natural events and bridge collapses: statistical insights in Italy]. In a publication by UNDRR, the collapse of bridges due to extreme weather events is described as a global issue. Earthquakes, erosion, and floods can cause bridge collapse, especially when earthquakes and floods occur simultaneously.[https://www.undrr.org/understanding-disaster-risk/terminology/hips/tl0204]

*Climate change does not eliminate the value of historical data, but it weakens the assumption that the past provides a reliable guide to future risk. Design standards based mainly on historical averages may not adequately account for changes in hazard frequency, intensity, duration, or geographic distribution*.

It is not that resilience thinking necessitates the immediate reconstruction of all bridges. It does mean that authorities should identify which structures are critical, which risks are changing fastest, and where failure would have the greatest social consequences. A risk-based approach could consider seven critical aspects:

- Hazard exposure: What hazards could affect the bridge and its approaches?
- Structural vulnerability: How might the bridge respond to flooding, scour, debris, heat, corrosion, landslides, or seismic activity?
- Network criticality: How many alternative routes exist, and how long would detours take?
- Social dependence: Which communities and essential services rely on the connection?
- Recovery capacity: How quickly could the route be inspected, repaired, or replaced?

- Cascading effects: What other systems could fail if the bridge becomes unusable?
- Future change: How may climate, land use, and population patterns alter risk?

## 2 Bridges as critical social infrastructure

The technical importance of bridges is inseparable from their social role. A bridge can determine whether residents reach work, children reach school, patients reach healthcare, and emergency responders reach affected communities. When a bridge fails, the burden is rarely distributed equally. People with private vehicles, flexible employment, digital access, or financial resources may find alternatives. Older people, people with disabilities, low-income households, isolated communities, and those dependent on public transport may face much greater disruption.

*Image credit and courtesy: Sachidanand Joshi*

A resilience assessment must therefore ask not only, "How much traffic does this bridge carry?" but also: Who depends on this connection? And who would be most affected by its loss? And which groups have the fewest alternatives? Along with the points, are evacuation routes accessible to people with different mobility needs? And how would disruption affect food, healthcare and social care? And building the capacity of local communities to identify critical and emergency routes in case of emergencies.

This is particularly important in rural, peripheral, and border regions, where a single bridge may connect communities to administrative, medical, or economic centers. It is also relevant in urban areas, where bridges can become bottlenecks during floods or major incidents.

***Resilience is therefore partly an issue of social justice, and investment decisions should not favour only routes with high economic returns. The goals should also be to protect connections vital to public safety, social inclusion, and territorial cohesion.***

## 3 The ecological dimension: space for water

Bridge resilience begins before construction. It depends on how rivers, floodplains, coastlines, and slopes are managed. One of the most important planning principles is to preserve space for natural processes. Floodplains are frequently treated as undeveloped land awaiting future use. In reality, they provide flood storage, slow the movement of water, support biodiversity, and reduce pressure on built infrastructure.

***An undeveloped floodplain is not empty land. It is natural infrastructure.***

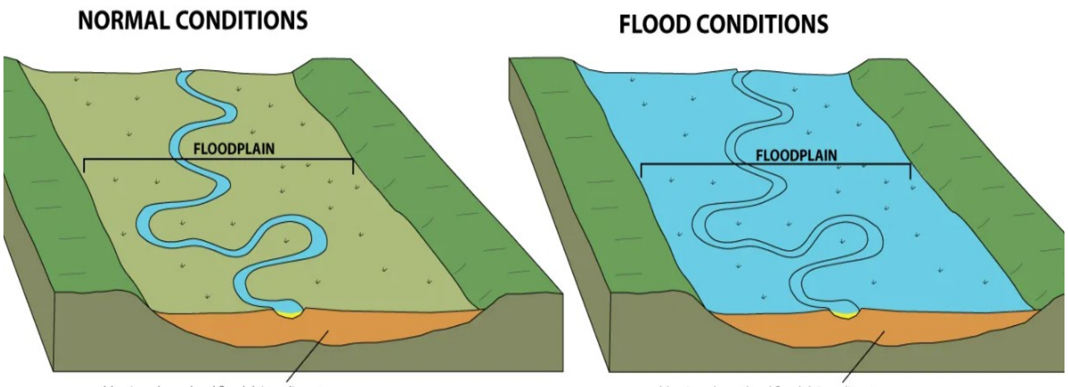



*Image credit and courtesy: https://www.fity.club/lists/suggestions/floodplain/*

Development that narrows river channels, removes wetlands, hardens riverbanks, or places buildings and roads in flood-prone areas can increase the pressure on bridges and surrounding settlements. A bridge designed in isolation cannot compensate for a landscape that has lost its capacity to absorb, slow, or safely redirect water. Nature-based approaches can complement structural engineering. These may include: restoring wetlands and riparian zones; reconnecting rivers with parts of their floodplains; protecting upstream soils and vegetation; reducing unnecessary surface sealing; restoring coastal dunes, marshes, and mangroves where appropriate; using vegetation to stabilize slopes; improving sediment management and creating designated overflow areas. Such measures do not remove the need for strong bridge design. They reduce the loads and risks that bridges must absorb. They also provide wider benefits for biodiversity, water quality, recreation, public health, and climate adaptation.

***A resilient bridge policy should therefore be integrated with river-basin planning, coastal-zone management, spatial planning, and ecosystem restoration.***

## 4 Rethinking design: from Resistance to Resilience

Traditional engineering often focuses on preventing failure under a specified design event. This remains essential, but resilience requires a broader perspective. A resilient bridge could be designed with several questions in mind: Can it withstand a range of foreseeable hazards, and can vulnerable components be inspected and repaired quickly? Further, can emergency vehicles use the route after an event, and, if the damage is isolated, can temporary access be established rapidly to avoid wider system failure? And if the bridge is adapted as risk conditions change?

This approach may lead to different design and maintenance choices, including increased hydraulic clearance; improved resistance to scour and debris impact; stronger and more adaptable foundations; elevated approaches in flood-prone areas; protected embankments and drainage systems; redundant routes for emergency access; modular bridge components; sensors and remote monitoring; predefined inspection and reopening protocols; stockpiled materials for rapid repair; designs that permit temporary crossings.

The right solution will vary by place. A bridge in a dense urban area may require redundancy and sophisticated monitoring. A rural bridge may require robust, low-maintenance construction and a clearly defined temporary access plan. A coastal bridge may require attention to corrosion, storm surge, and long-term sea-level rise.

***Resilience is not a single technical feature. It is a performance objective that should be embedded across planning, design, construction, operation, maintenance, and decommissioning.***

## 5 The Bridge Resilience System

Many authorities already use Bridge Management Systems to record conditions, schedule inspections, prioritize maintenance, and manage budgets. These systems are valuable, but they often focus primarily on structural condition and asset performance. A Bridge Resilience System should expand this scope. It should connect asset data with hazard information, network analysis, emergency planning, land-use decisions, and social vulnerability, and include Asset condition (structural condition and deterioration; foundation and scour risk; material degradation and corrosion; maintenance history; and age and remaining service life. And in terms of Hazard information: flood depth and velocity; debris-flow and landslide exposure; storm surge and coastal erosion; wildfire and heat exposure; seismic risk; compound and cascading hazards. For social and territorial vulnerability aspects such as population dependence, demographic characteristics, public transport availability, access needs of vulnerable groups, rural isolation, and service dependence, and clarity on recovery planning, i.e., inspection procedures; emergency contracts; temporary crossing options; repair materials and equipment; communication protocols and responsibilities across agencies.

The value of such a system is not simply improved information. It is improved decision-making. It enables authorities to identify which investments will most effectively reduce risk and protect essential connectivity.

***Fragmented responsibilities often weaken bridge resilience.***

Rivers cross municipalities and national borders. Roads may be managed at the local, regional, or national level. Emergency services, water authorities, transport agencies, and environmental departments may operate under different mandates and use different data systems.

***A bridge can therefore become a point where governance gaps become physical failures.***

Effective resilience planning requires cooperation across: local and regional authorities; transport and infrastructure agencies; river-basin organizations; environmental and spatial-planning bodies; emergency and civil-protection services; public health authorities; utility providers; communities and civil-society organizations; private operators and contractors; and neighbouring countries in cross-border regions.

Coordination should be established before a disaster. Authorities should agree on who monitors risk, who can close a bridge, who communicates with the public, who leads inspections, and who funds emergency repairs.

Cross-border cooperation is particularly important in European regions where bridges connect countries, municipalities, or administrative territories. A bridge failure can create consequences on both sides of a border, while differences in standards, procurement rules, and emergency procedures may delay action.

A resilience-oriented governance model should include joint exercises, interoperable data, shared risk assessments, and pre-agreed emergency arrangements.

*Is financing resilience a value investment?: Yes*

Resilience is often perceived as an additional cost for an event that may never occur. This framing encourages short-term savings and under-investment in prevention. Yet the apparent saving may be illusory, noting its role in emergency response; evacuation and rescue; temporary transport arrangements; business interruption; supply-chain disruption; loss of local revenue; increased travel time and social isolation; loss of life and long-term well-being.

Life-cycle appraisal should include these wider consequences. It should compare not only construction costs, but also the cost of disruption under different risk scenarios. It is anticipated that the funding mechanisms could support multiple dimensions, as noted in the visual below.

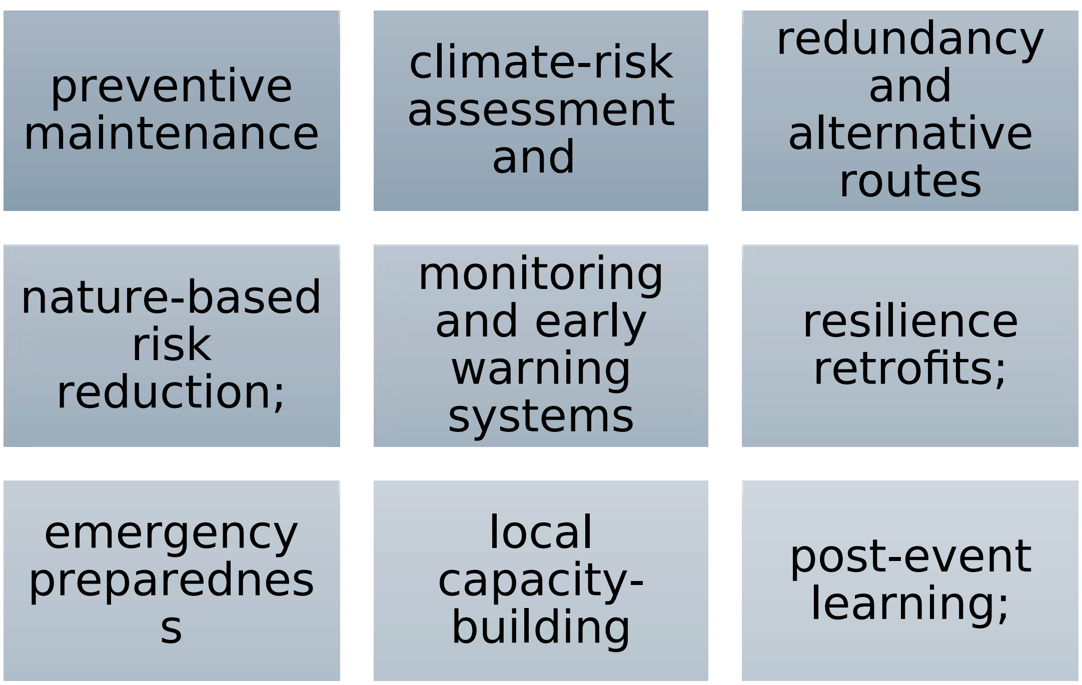



Figure: Key dimensions that financial commitments can consider in a long-term resilience-focused strategy

Public investment decisions, therefore, create new exposure. Building a bridge that encourages settlement in an active floodplain may generate short-term access while increasing long-term risk. Infrastructure investment must be aligned with land-use policy and ecosystem protection.

Every bridge failure, near miss, and extreme event should generate institutional learning. Reviews should not focus only on identifying individual errors. They should examine how decisions, standards, maintenance practices, land-use choices, and communication systems interact.

Last month, extreme rainfall and related hazards in Nepal led to the collapse or severe damage of nearly 80 bridges, along with widespread damage to roads, embankments, and settlements. [https://vajiramandravi.com/current-affairs/nepal-flood/]

*Image credit and courtesy: apnews.com*

*Image credit and courtesy: indiatvnews.com*

*Image credit and courtesy: independent.co.uk*

*Image credit and courtesy: Yahoo News*

Was the hazard correctly understood? Were warning signs identified? Were inspection and closure procedures adequate? Did agencies share information effectively? Were vulnerable communities reached? Were alternative routes available? Did land-use decisions increase exposure? Did the bridge perform as expected? How quickly was connectivity restored? And what should change in standards, planning, or investment?

This learning should be incorporated into design guidance, procurement, emergency plans, and professional training. It should also be shared across regions. (https://www.indiawaterportal.org/climate-change/nepal-flood-assessing-cross-border-resilience-and-risks-along-shared-himalayan-river)

***A resilient system is not one that never experiences failure. It anticipates failure, limits its consequences, learns from it, and adapts.***

## 6. Key recommendations

- ***Establish bridge resilience as a formal infrastructure objective***

National and regional authorities should define resilience, alongside safety, functionality, sustainability, and efficiency, as a core requirement for critical bridges. Existing management systems should include hazard exposure, network criticality, social vulnerability, recovery capacity, and climate projections.

- ***Identify strategically critical bridges***

Authorities should map bridges whose failure would isolate communities, disrupt emergency access, or interrupt essential supply chains. These bridges should receive priority for assessment, retrofit, and contingency planning.

Bridge decisions should be assessed alongside floodplain development, watershed change, coastal management, ecosystem restoration, and settlement patterns.

- ***Protect natural infrastructure and Design for exceedance and rapid recovery***

Floodplains, wetlands, river corridors, dunes, and other ecosystems should be recognized as part of the infrastructure system that protects bridges and communities.

Standards should consider how bridges behave when hazards exceed conventional assumptions. Designs should include strategies for inspection, repair, temporary access, and reopening.

- ***Build redundancy into critical networks and use inclusive risk assessment***

Where a bridge is the only connection to essential services, authorities should assess alternative routes, emergency crossings, and other forms of network redundancy.

Communities, emergency responders, public health professionals, and vulnerable groups should contribute to identifying critical connections and defining acceptable recovery times.

- ***Strengthen cross-border coordination and reform economic appraisal***

Neighboring jurisdictions should develop shared protocols for monitoring, closure, inspection, communication, and repair of bridges with regional or international importance.

Cost-benefit assessments should include social disruption, delayed emergency response, loss of life, ecosystem services, and long-term economic consequences.

In line with the above suggestions, creating a set of resilience indicators such as time required to restore access, availability of alternative routes, percentage of critical bridges assessed for climate risk, number of bridges with emergency response plans, condition of river corridors and floodplains, accessibility for vulnerable populations, frequency of resilience exercises, and maintenance backlog for strategic bridges remains critical.

**Bridge resilience should be reviewed periodically as hazards, technologies, land use, demographics, and traffic patterns change.**

## *7. Looking Ahead*

Bridges are among the most visible expressions of connectivity. They connect people to services, communities to markets, and regions to one another. During a disaster, however, their deeper role becomes clear: they connect affected populations to rescue, healthcare, food, shelter, and recovery. This is why bridge policy cannot remain confined to structural engineering or routine asset management. A bridge is embedded in a landscape, a transport network, a community, and a governance system. Its resilience depends on all of these dimensions.

The changing disaster landscape demands a shift in thinking. Hazards are increasingly dynamic, compound, and difficult to predict through historical data alone. Infrastructure must therefore be planned for uncertainty, designed for adaptation, and managed in light of the consequences of failure. The transition from Bridge Management Systems to Bridge Resilience Systems offers a practical framework for this change. It connects engineering performance with emergency access, social vulnerability, ecosystem function, land-use planning, and long-term public value.

The aim is not to build infrastructure that attempts to defeat natural processes. It is to understand those processes, reduce unnecessary exposure, and design systems that can continue to protect essential functions when conditions become extreme.

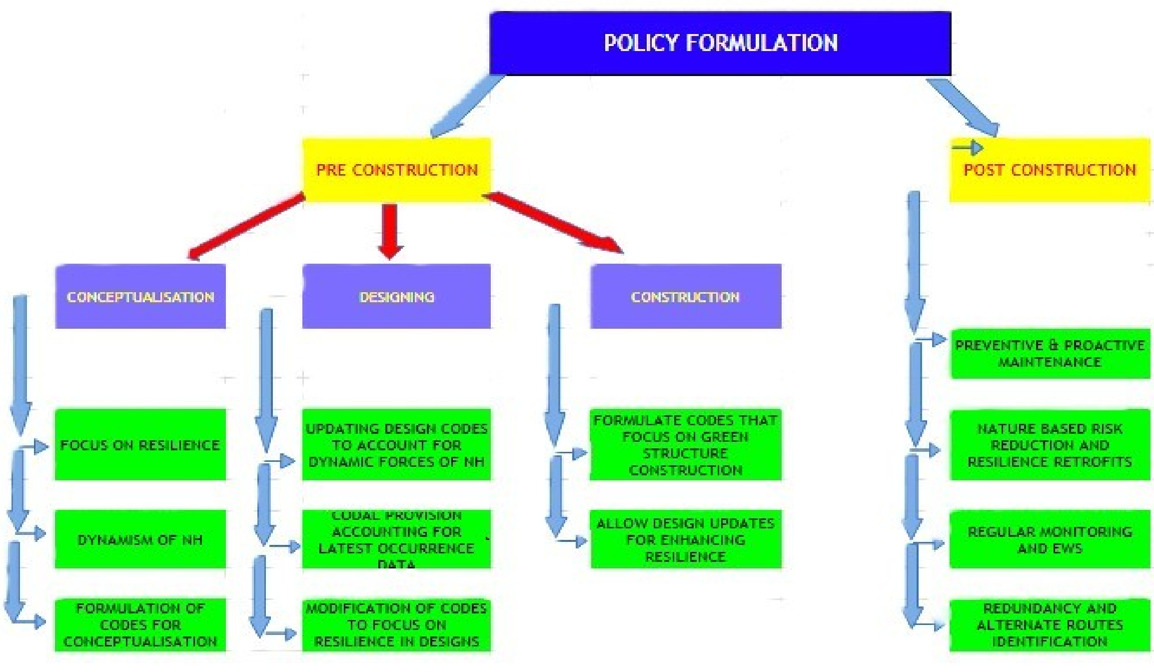
The bridges built and managed today should do more than connect two points under normal conditions. They should preserve or rapidly restore connectivity when communities are disrupted.

That is the meaning of critical infrastructure resilience. It is also a foundation for safer, more sustainable, and just development.

**Let's think about moving from managing bridges as isolated assets to governing them as resilient, connected, and socially essential systems.**

Focusing only on bridges; following areas will need changes, beginning with key policies changes, technical and knowledge base updates, implementation monitoring aimed for zero tolerance via governance consolidation.

- **Policy formulation** aimed to enhance resilience starting with conceptualisation, designing, construction, full life maintenance are urgently required to be put in place. Every Country need to bring such changes. We need to plan for the dynamism in frequency and severity of natural hazards. Recent unpredictable events revealed that material loss exceeds  $2.5 billions. Add the loss of over 1340 human lives. Investing in resilience is needed. [https://www.indiatvnews.com/news/world/nepal-observes-day-of-national-mourning-for-lives-lost-in-devastating-floods-2026-09-07-1053525]




- **Technical and knowledge base** needs to be updated. Established design codes rely heavily on forces due to natural hazards based on established historical narrative for frequency and severity. Such reliance is outdated. Dynamism of frequency and severity of natural hazards needs to be challenged by allowing our design philosophies to incorporate Dynamism. Forces of natural hazards occurrences will be accounted based on the highest severity and most frequent occurrence. Designers will need flexibility to adopt such changes in their design practices. Construction practices will need to accommodate resilience-focused approach. The system to award lowest bidders will need to be replaced by awarding the safest resilient designs. Designs incorporating minimal carbon footprint should be encouraged.

- Our **maintenance budgets** need incorporate enhancing resilience every few years and the same need to be included in life-cycle analysis. Inspection of bridges will need to change from being reactive to a very proactive approach to maintaining resilient bridges. Management systems need to be replaced with Resilience Systems.

- **Governance** procedures will be based on zero tolerance. Safety limits will be enforced through regular monitoring process by all government departments involved in design approval, construction monitoring, regular inspection and maintenance aimed to maintain resilience. The incremental changes in forces due to natural hazards occurrences will need to be incorporated in all facades of bridge life-cycle.

***LETS LEARN FROM OUR FAILURES. LETS INCORPORATE RESILIENCE IN EVERY ASPECT OF BRIDGE MANAGEMENT BY ADOPTING BRIDGE RESILIENCE SYSTEM***