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REVIEW ARTICLE

A Review on Seismic Resilience of Roadway Infrastructure

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ABSTRACT - This paper addresses the seismic resilience of roadway infrastructure, exploring methods to assess damage risk and enhance resilience to earthquakes. Ground motion prediction models, fragility curves, and damage scenarios are employed for risk assessment, while strategies such as seismic design codes, base isolation, damping systems, and flexible pavement designs are proposed for resilience improvement. Case studies offer insights into the effectiveness of these strategies. Technological innovations and advancements in materials and construction contribute to seismic resilience to a great extent. Future research should focus on refining ground motion prediction models and vulnerability assessment techniques. Policymakers and stakeholders must recognize the long-term benefits of investing in resilient infrastructure for community safety.

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INTRODUCTION

The vulnerability of roadway infrastructure to seismic events poses a significant threat to societies and economies worldwide. Earthquakes can unleash substantial destructive forces that not only damage roadways themselves but also trigger cascading effects on essential services, transportation networks, and daily life. In the aftermath of such events, communities often face prolonged disruptions, hindering emergency response, rescue operations, and recovery efforts. As a result, there is a pressing need to comprehensively understand and address the seismic resilience of roadway infrastructure to minimize the far-reaching impacts of earthquakes [1]. Recognizing the potential devastation caused by seismic events, it becomes imperative to delve into a systematic and rigorous investigation of the seismic vulnerability and resilience of roadway infrastructure. This exploration is crucial not only for preventing costly damages but also for safeguarding human lives and livelihoods. By studying the behavior of roadways during seismic events, researchers and policymakers can formulate effective strategies to mitigate the consequences of earthquakes [2].

Despite ongoing efforts to assess and enhance seismic resilience in roadway infrastructure, there remains a lack of specificity in addressing key issues and defining a clear scope and objective in current research. This study aims to identify and emphasize specific challenges hindering the seismic resilience of roadways, focusing on the development of more accurate ground motion prediction models and advancements in vulnerability assessment techniques. By addressing these gaps, the research seeks to contribute to the effective implementation of strategies such as seismic design codes, base isolation, damping systems, and flexible pavement designs, ultimately reducing future losses and enhancing community safety. Additionally, the paper will dig into case studies and performance assessments that

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shed light on real-world examples of seismic events impacting roadway infrastructure. In the pursuit of understanding seismic resilience, the paper will also explore the role of technological advancements and tools that aid in monitoring, modeling, and predicting seismic impacts. Furthermore, it will identify emerging trends, challenges, and potential directions for future research in this domain, while considering the broader contexts of policy and regulatory frameworks.

By undertaking this comprehensive review, the paper intends to contribute to the existing body of knowledge by consolidating insights from diverse studies, thereby facilitating a more holistic comprehension of seismic resilience in roadway infrastructure. The knowledge gleaned from this endeavor can inform decision-makers, engineers, and planners in devising strategies that enhance the capacity of roadways to endure seismic events and promote rapid recovery. The paper delves into various critical aspects including Seismic hazard assessment, Seismic vulnerability assessment, Seismic resilience enhancement strategies, Case studies and performance assessment, Technological innovations and tools, Future directions and challenges, and Policy as well as regulatory frameworks.

Seismic Hazard Assessment

Seismic hazard assessment plays a crucial role in understanding the potential risks posed by earthquakes to roadway infrastructure. This process involves identifying potential seismic sources and estimating the ground motion affects that can be expected during seismic events [3]. Several studies have been developed on ground motion prediction models for specific regions. Ground motion prediction models (GMPMs) are widely utilized tools in seismic hazard assessment as they provide valuable information about the intensity and characteristics of ground shaking. GMPMs enable engineers and researchers to estimate essential ground motion parameters, including peak ground acceleration (PGA) and spectral acceleration (SA), which are vital for seismic design and evaluation of road infrastructure. These parameters help in determining the level of seismic forces that roadways might experience during an earthquake, guiding engineers in developing resilient designs and retrofitting strategies.

Various studies have been contributed to the development of GMPMs tailored to specific regions with known seismic activity. These models are based on extensive seismic data and statistical analyses of historical earthquake records. The regional GMPMs consider some factors such as local geology, fault characteristics, and seismicity patterns, allowing for more accurate and region-specific hazard assessments [4; 5].

Tang et al. [5] proposed an adaptability assessment model for seismic resilience of roadway infrastructure which is graphically represented in Figure 1. The target node having adaptive capacity is marked in red and has five parent nodes represented in green, namely, earthquake intensity, technology, organization, economic variables, and social factors. Earthquake intensity is influenced by epicentral distance and earthquake magnitude. Technology is influenced by normative operation, professional staff, maintenance routine, advanced technology, and earthquake history. Organization is influenced by earthquake history, training drills and rehearsals, contingency mechanisms, and leadership. Economic variables are affected by operation and maintenance funds, government investment decisions, financial reserves, and local economic development. Social factors are determined by relevant information and public awareness, where public awareness is further influenced by social information sharing and the level of residents' culture.

Seismic Vulnerability Assessment

Seismic vulnerability assessment plays a crucial role in understanding the susceptibility of roadway infrastructure to seismic events. It involves the quantitative evaluation of how different components of the road system, such as bridges, pavements, and embankments, may respond to ground shaking during earthquakes. By conducting such assessments, engineers and policymakers can identify vulnerable areas and prioritize retrofitting and resilience enhancement measures. Various vulnerability indicators and assessment techniques have been proposed in the literature, each offering valuable insights into the seismic performance of roadways:

Fragility Curves: Fragility curves express the probability of exceeding certain damage levels for a given seismic intensity measure. These curves are essential tools in quantifying the vulnerability of specific components or types of road infrastructure. Researchers have been applied fragility curves to bridges, pavements, and other structures to estimate their damage probabilities under different seismic scenarios [6; 7].

Vulnerability Indices: Vulnerability indices are composite measures that combine multiple parameters to assess the overall vulnerability of a roadway system. These indices can account for factors such as structural strength, site characteristics, and maintenance conditions [8]. They offer a comprehensive view of the system's resilience and guide decision-making in allocating resources for improving vulnerable road segments [9].

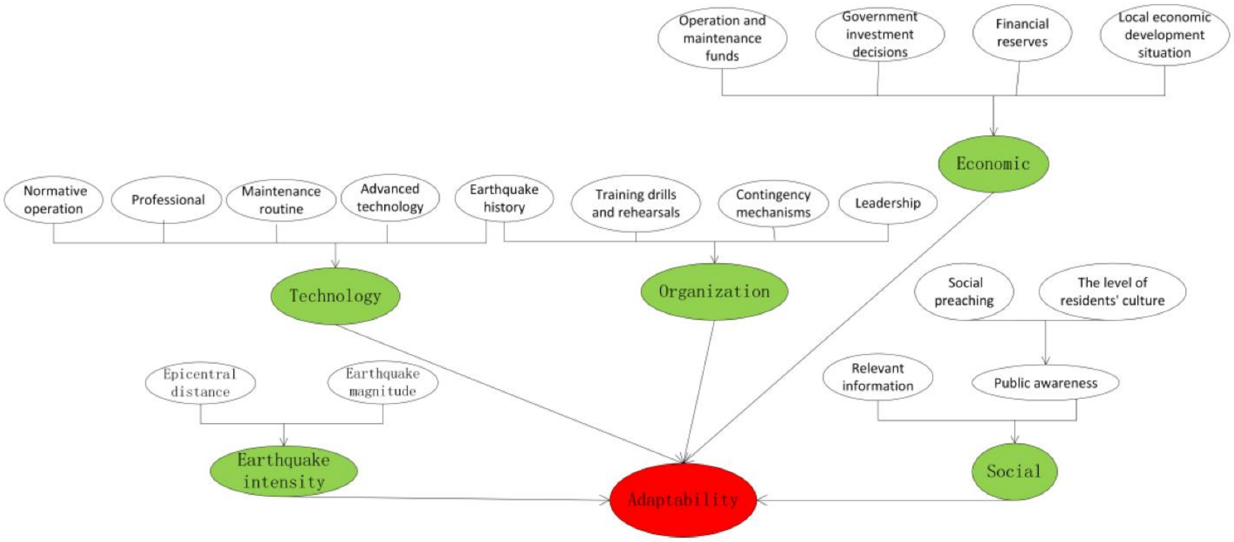

Figure 1. Adaptability assessment model for critical infrastructures [5]

Damage Scenarios: Damage scenarios involve simulating potential earthquake events and analyzing their effects on roadway infrastructure. Through computer modeling and simulations, engineers can predict the likely damage patterns and critical failure points in the road system. Such scenarios help to identify the weaknesses and design targeted mitigation strategies [10; 11].

Nath et al. [12] proposed a vulnerability assessment protocol for earthquake vulnerability of Kolkata, India necessitating systematic assessment of seismic vulnerability by identifying those factors contributing to seismic risk in terms of socioeconomic and structural aspects (Figure 2). Although it is mainly related to seismic vulnerability of city area, it gives insights about the vulnerability of roadways in the city area. It is important to note that seismic vulnerability assessment should consider regional seismicity, soil conditions, and the specific engineering characteristics of the road network. Real-world data from past earthquakes are valuable for calibrating and validating vulnerability models, ensuring their accuracy and reliability.

As research in this field continues to advance, the integration of cutting-edge technologies, such as remote sensing and machine learning, holds promise for enhancing the precision and efficiency of seismic vulnerability assessment for roadway infrastructure [13; 14].

Case studies have shown that some road infrastructure, such as bridges and tunnels, are more vulnerable to seismic events than others [4; 15].

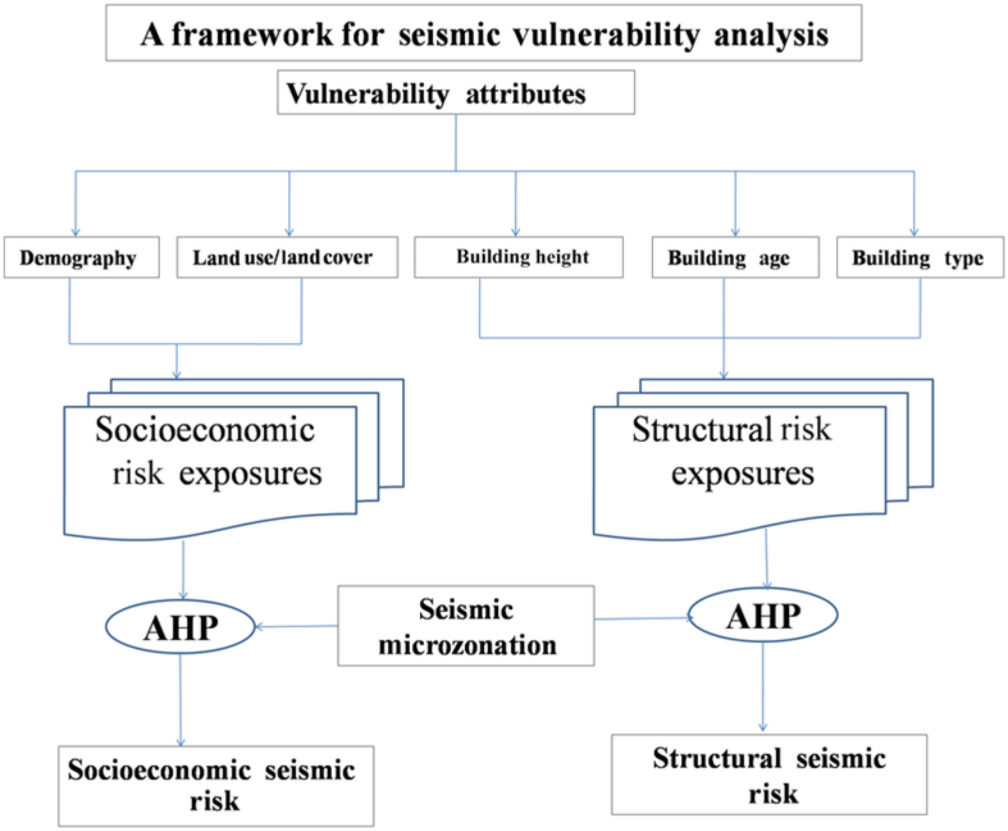

Figure 2. Framework for seismic vulnerability assessment for Kolkata city, India [12]. [AHP = Analytic Hierarchy Process]

Seismic Resilience Enhancement Strategies

Seismic resilience enhancement strategies are essential for fortifying roadway infrastructure to withstand the impact of seismic events effectively. Extensive research works in the field have proposed various approaches to enhance the seismic performance of roads and highways, mitigating the adverse effects of earthquakes [2; 16]. The following key strategies have been extensively studied and demonstrated their effectiveness in improving the seismic resilience of roadway infrastructure:

Seismic Design Codes and Guidelines: Implementing robust seismic design codes and guidelines is a fundamental strategy to enhance the seismic resilience of roadway infrastructure. These codes provide engineers with essential parameters and criteria for designing roads that can withstand specific seismic forces [17]. By integrating these provisions into road design, engineers can ensure that critical components, such as bridges, overpasses, and embankments are more resistant to seismic shaking. As a result, the overall structural integrity of the roadway is improved, reducing the risk of damage during earthquakes [18].

Base Isolation: Base isolation is a sophisticated technique that decouples the superstructure of a road or bridge from its foundation, allowing it to move independently during seismic shaking. This isolation effectively reduces the transmission of seismic forces to the roadway, thus minimizing structural damage. It has been successfully employed in various seismic-prone regions to protect vital transportation networks. Base isolation can significantly increase the seismic resilience of roadway infrastructure by preserving the road's functionality even after a significant earthquake [19; 20]. An example of the application of base isolation in seismic resilience is the San Francisco-Oakland Bay Bridge in California, USA. The eastern span of the Bay Bridge underwent a seismic retrofitting project that included the implementation of base isolation. The new span, completed in 2013, utilized a state-of-the-art seismic retrofitting system called seismic isolation bearings. These bearings allow the bridge to move independently of the ground motion during an earthquake, effectively decoupling the superstructure from its foundation and minimizing the transmission of seismic forces. The base isolation technique significantly enhances the bridge's ability to withstand seismic events, reducing the risk of damage and ensuring the safety of commuters [21].

Damping Systems: Damping systems are devices which are installed within the road structure to dissipate seismic energy and to control vibrations during an earthquake. These systems help to reduce the dynamic response of the roadway, preventing excessive movement and potential damage. By incorporating damping systems into the design, the seismic resilience of roadway infrastructure is enhanced ensuring a quicker recovery and minimizing downtime after seismic events [21a; 22].

Flexible Pavement Designs: Traditional rigid pavement designs can be vulnerable to seismic forces, leading to cracks and other forms of damage. In contrast, flexible pavement designs offer greater resilience during earthquakes by accommodating ground movements and distributing stresses more efficiently. By adopting flexible pavement designs, roadways can better withstand seismic shaking, resulting in reduced damage and maintenance costs [23; 24]. Table 1 describes the important strategies to be adopted to have effective seismic resilience in roadways. One notable example of the application of flexible pavement designs for seismic resilience is the use of Fiber-Reinforced Asphalt Mixtures (FRAM) in earthquake-prone regions. The incorporation of fibers, such as polyester or polypropylene, enhances the flexibility and ductility of the asphalt mix, allowing it to better withstand ground movements during seismic events. Flexible pavement designs offer greater resilience during earthquakes by accommodating ground movements and distributing stresses more efficiently. The framework for the design of sustainable flexible pavement by Asres et al. [24] considers resilience principles in flexible pavement design.

These seismic resilience enhancement strategies have shown promising results in safeguarding roadway infrastructure during seismic events. Implementing a combination of these approaches, tailored to the specific geological and structural characteristics of each region, can significantly reduce the vulnerability of road networks to seismic hazards

Table 1. Seismic resilience strategies for mitigation of risks in roadway infrastructures

Sl no.	Strategy to be adopted	Description
1.	Retrofitting	Strengthening existing roadway structures to withstand seismic forces e.g., using energy dissipating devices, column jacketing etc..
2.	Base isolation	Installing isolators between the foundation and the superstructure to absorb seismic energy. Following the 1989 Loma Prieta earthquake, the San Francisco City Hall underwent extensive seismic retrofitting, including the installation of base isolators. The isolators placed beneath the building's foundation allow it to move independently during seismic events, protecting the iconic structure from severe damage.
3.	Damping systems	Introducing devices to absorb and dissipate seismic energy, reducing vibrations.
4.	Seismic design standards	Implementing specific design codes that account for seismic resilience in new road construction. Eurocode 8 provides European countries with a common set of seismic design standards. EN 1998 includes specific guidelines for seismic design, assessment, and retrofitting of structures to ensure their safety during earthquakes.
5.	Soil stabilization	Improving soil conditions to minimize ground movement during earthquakes.
6.	Landslide prevention	Implementing measures to prevent landslides triggered by seismic activity near roadways. Soil nailing involves reinforcing the slope with grouted soil nails or rods to enhance stability. This method is particularly effective in cohesive soils.
7.	Emergency response planning	Developing protocols for post-earthquake actions, including rapid assessment and road reopening procedures. For example, Japan has an advanced earthquake early warning system provided by the Japan Meteorological Agency. The system detects initial seismic waves to provide seconds to minutes of warning before the

		more damaging waves arrive, allowing individuals to take protective actions and automated systems to initiate shutdown procedures.
8.	Maintenance and inspection	Regularly checking and maintaining road infrastructure to ensure its resilience over time. Regularly inspecting road surfaces for cracks, potholes, or other signs of distress that may compromise the pavement's integrity during seismic events. Performing routine maintenance activities, such as sealing cracks and repairing damaged sections, to ensure the overall stability of the roadway.
9.	Public awareness programs	Educating the public about earthquake preparedness and response when using roadways.
10.	Collaboration with experts	Partnering with seismic engineers and geologists to develop effective resilience strategies.

Case Studies and Performance Assessment

Case studies of roadways or highway systems in seismic-prone regions can provide valuable insights into the performance of resilient road infrastructure during historical seismic events. By analyzing real-world examples, researchers can better understand the effectiveness of seismic resilience strategies and identify areas for improvement.

One notable case study is the performance assessment of road infrastructure during the Wenchuan earthquake in China, which occurred on May 12, 2008. This earthquake had a magnitude of 7.9 and caused extensive damage to the region's transportation networks. Studies, such as the one conducted by Wei et al. [15] focused on evaluating the seismic vulnerability and resilience of highway bridges in the affected area. It built three resilience assessment indices, namely, the overall integrity, overall connectivity and effective connectivity with the complex network and resilience framework, to investigate the road network resilience. The objective of this research was to analyze the damage patterns that observed in different types of bridges and to assess the effectiveness of various design features in mitigating the earthquake's impact.

Another relevant case study is the performance assessment of Great East Japan Earthquake occurred on March 11, 2011. This earthquake had also magnitude of 7.9 and severely affected the expressway system in the region. Research conducted by Ishibashi et al. [25] investigated the damage to the expressway's elevated structures and evaluated the retrofitting measures implemented to improve seismic resilience. The study provided valuable lessons on retrofit strategies and their effectiveness in enhancing the seismic performance of roadway infrastructure.

In addition, to evaluate Chile's road infrastructure after the 2010, Maule earthquake [26] offer critical insights for designing and retrofitting resilient road networks.

Overall, case studies and performance assessments of roadway infrastructure in seismic-prone regions are fundamental to understanding the behavior of resilient roads during earthquakes. The knowledge acquired from such studies helps to observe and perform future engineering practices, policy development, and disaster management strategies aimed at enhancing the seismic resilience of vital transportation networks [15]. These studies can help to identify the strengths and weaknesses of current seismic resilience to guide in measurement and information of future research directions.

Technological Innovations and Tools

Emerging technologies and tools play a crucial role in advancing the field of seismic vulnerability assessment and resilience enhancement for roadway infrastructure. One noteworthy example is the probabilistic approach. This approach offers a comprehensive method to evaluate the seismic resilience of road asset management by considering the cumulative impact of disruptions on the overall system performance. By integrating probabilistic models and performance-based assessments, this methodology provides valuable insights into the vulnerabilities and potential failure modes of road networks under seismic stress [27].

In addition to innovative assessment methodologies, continuous advancements in materials and construction techniques which offer promising opportunities to improve the seismic performance of roadway infrastructure. Heiran [28] has investigated the application of advanced high-strength and ductile materials in road construction. Such materials exhibited enhanced energy dissipation and deformation capacity, thereby reducing the risk of structural damage during earthquakes. Furthermore, implementing innovative construction techniques, such as seismic isolation and energy-absorbing devices, as studied by Shekhar et al. [29], could significantly enhance the seismic resilience of bridges and other critical elements within the roadway network.

Moreover, the advent of advanced sensing technologies and real-time monitoring systems allows for better understanding of road behavior during seismic events. Whelan et al. [30] and Sonbul & Rashid [31] presented the findings where distributed sensor networks were deployed to monitor the response of bridge structures under earthquake-induced vibrations. Such data-driven insights can aid in refining seismic design and retrofit strategies, ensuring more effective and resilient roadway infrastructure.

Furthermore, the integration of Geographic Information Systems (GIS) and remote sensing technologies have been proved beneficial in mapping the spatial distribution of seismic hazards and identifying vulnerable regions within roadway networks. By incorporating seismic risk maps and geospatial data, decision-makers can prioritize investments in retrofitting and strengthening projects in areas with higher seismic risks, as demonstrated by Van Westen [32].

Izumi et al. [33] suggested 30 innovations including GIS and remote sensing, Drone, Doppler radar, Disaster prevention radio and telemetry system, use of social networking service, use of disaster resilient materials, introduction of seismic codes and earthquake early warning systems etc. for disaster risk reduction. Drone (Figure 3), as an example, can access hard-to-reach areas and perform data-gathering tasks that are otherwise unsafe or impossible for humans. Drones cannot save people's lives that much, but possibility transportation of emergency medicine, foods, blood etc. to the affected areas would help in reducing death and affected people.

These technological innovations and tools have been paving the way for more informed decision-making processes, enabling engineers, policymakers, and infrastructure managers to design and maintain roadway networks that are better equipped to withstand seismic challenges [34; 35]. Embracing these advancements is crucial to enhancing the overall resilience of roadway infrastructure and safeguarding the well-being of communities in seismic-prone regions. Moreover, advancements in materials and construction techniques can contribute to improve seismic performance of roadway infrastructure.

Figure 3. Drone, a disaster risk management tool (Source: https://www.meer.com/en/67584-scary-drones)

Future Directions and Challenges

Despite significant progress in the field of seismic resilience of roadway infrastructure, several challenges persist, warranting further exploration and research. One prominent area of focus is the development of more accurate ground motion prediction models. Improving the precision of these models is crucial for better understanding the potential seismic forces that road infrastructure may be encounter. Researchers and engineers can work towards integrating data from recent seismic events into these models to enhance their accuracy and reliability [36; 37].

In addition to ground motion prediction, advancing vulnerability assessment techniques is vital. Current methodologies have made substantial strides in identifying vulnerable road segments, but more sophisticated approaches are needed to comprehensively evaluate the interdependencies between different infrastructure elements and their response to seismic events. Utilizing advanced analytical tools, such as finite element analysis and advanced numerical simulations, can provide deeper insights into the structural behavior of roadways during earthquakes [38-40].

Another key challenge is the implementation of seismic resilience measures. While the technical solutions for enhancing seismic resilience exist, their effective application faces obstacles such as limited funding and lack of political will. Policymakers and stakeholders must recognize the long-term benefits of investing in resilient infrastructure to reduce future losses and enhance community safety [41-43]. Public-private partnerships and innovative financing mechanisms can be explored to overcome funding constraints.

Furthermore, the integration of seismic resilience into existing infrastructure planning and decision-making processes is crucial. Collaboration between structural engineers, urban planners, and policymakers is necessary to ensure that seismic considerations are adequately incorporated at every stage of roadway development, from design and construction to maintenance and retrofitting [41].

Future research should focus on addressing these challenges and improving the practical applications of seismic resilience measures. Multidisciplinary studies that involve collaboration between civil engineers, seismologists, social scientists, and policymakers can yield comprehensive solutions for improving the seismic performance of roadway infrastructure. It is essential to prioritize research that directly informs policy and practice, enabling the effective implementation of seismic resilience measures and enhancing the overall safety and sustainability of road networks [2; 23].

In conclusion, while considerable progress has been made in the field of seismic resilience of roadway infrastructure, there are still several challenges to be addressed. By advancing ground motion prediction models, vulnerability assessment techniques, and resilience implementation strategies, and fostering collaboration between stakeholders, we can pave the way for safer and more resilient roadways in earthquake-prone regions.

Policy and Regulatory Frameworks

Policy and regulatory frameworks play a pivotal role in determining the seismic resilience of roadway infrastructure. The effectiveness of existing policies directly influences the successful implementation of seismic resilience measures. Therefore, it is crucial to conduct a comprehensive examination of the current policies and regulations to identify their strengths, weaknesses, and areas for improvement. Different organizations and committees in different countries play the roles in executing policy and regulatory frameworks related to seismic resilience of roadways and buildings (Table 2).

Table 2. Policy and regulatory frameworks related to the seismic resilience of roadways in different countries

Country/ Region	Policy/Regulation title	Description	References
United States	Federal Highway Administration (FHWA) Seismic Design and Retrofitting Guidelines	Provides guidelines for designing and retrofitting roadways to withstand seismic events. FHWA works with state transportation agencies to ensure seismic resilience in road infrastructure.	[44]
United States	National Earthquake Hazards Reduction Program (NEHRP)	NEHRP is a federal program aimed at reducing the impacts of earthquakes on infrastructure and communities. It involves multiple agencies, including the Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST), and the U.S. Geological Survey (USGS). These agencies contribute to seismic research, engineering guidelines, and code development that influence roadway resilience policies	[45]
Japan	Japan: Road Traffic Act and Road Transport Vehicle Act Amended	Encompasses regulations and standards for road construction, maintenance, and disaster preparedness, including seismic resilience. Japan has stringent seismic design standards due to its high earthquake risk.	[46]
New Zealand	New Zealand Transport Agency (NZTA) Earthquake-prone and Seismic-Prone Bridge Assessment and Strengthening	NZTA outlines guidelines for assessing and strengthening bridges against seismic events to ensure their resilience and safety.	[47]
Chile	Ministry of Public Works (MOP) Seismic Design Guidelines for Roads	Chile is located in a seismically active area, and MOP has established guidelines to ensure roadways are designed and constructed to withstand earthquakes.	[48]
Italy	Seismic Risk Reduction Legislation	Italy's seismic regulations cover various aspects of infrastructure, including roadways. The regulations ensure that roads are designed and maintained to mitigate seismic risks.	[49; 50]
Turkey	Turkish Seismic Code for Buildings and Earthquake-Resistant Design	While focused on buildings, Turkey's seismic code also influences roadway design to a certain extent, considering the earthquake-prone nature of the region.	[51; 52]
Nepal	National Building Code (NBC) and Road Standards	NBC includes seismic design provisions for infrastructure, and road standards also consider seismic resilience due to Nepal's vulnerability to earthquakes.	[53; 54]
China	China Seismic Design Code for Highways and Bridges	China's seismic design code for highways and bridges ensures that road infrastructure is resilient to earthquakes in a region with varying levels of seismic activity.	[55; 56]
European Union	European Committee for Standardization (CEN) Standards for Roadway Infrastructure	CEN develops standards for various aspects of roadway infrastructure, including seismic resilience considerations for regions prone to earthquakes.	[57]

In many countries, including Bangladesh, government agencies and transportation authorities have developed policies that aim to address seismic resilience in roadway infrastructure. These policies often include guidelines for seismic design, construction standards, and retrofitting of existing roads to enhance their ability to withstand seismic forces. However, the effectiveness of these policies can vary based on several factors, including their clarity, enforcement mechanisms, and alignment with the latest seismic research and engineering practices [27].

One critical aspect to consider is the integration of seismic considerations into the entire lifecycle of roadway infrastructure. From the planning and design phases to construction, maintenance, and rehabilitation, policies must ensure that seismic resilience is a continuous consideration. Proper budget allocation and allocation of resources are also essential to implement these policies effectively.

Additionally, engaging stakeholders from the engineering community, academia, industry, and local communities is crucial in formulating and revising policies. Collaboration among these stakeholders can lead to a more informed and holistic approach to seismic resilience, addressing site-specific challenges and local knowledge.

To identify potential improvements in policy and regulatory frameworks, research and case studies from other seismic-prone regions with successful seismic resilience practices can be analyzed. Learning from best practices and success stories can help inform the revision of policies in the context of the specific region under consideration.

A noteworthy example of effective policy implementation can be found in Japan, a country with extensive experience in managing seismic risks. Japan's robust seismic regulations and guidelines for infrastructure have significantly contributed to its ability to withstand frequent earthquakes. Research on Japan's policies and their outcomes could offer valuable insights for countries like Bangladesh aiming to enhance their roadway infrastructure's seismic resilience.

In decision, robust policy and regulatory frameworks are integral to promoting seismic resilience in roadway infrastructure. Through a comprehensive examination of existing policies, identification of their strengths and weaknesses, and learning from best practices, authorities can make informed decisions and suggest improvements to ensure a more resilient roadway network capable of withstanding seismic challenges.

CONCLUSION

The seismic resilience of roadway infrastructure is absolutely crucial in mitigating the devastating impact of earthquakes on transportation networks. This review paper highlights the critical aspects of seismic resilience, including seismic hazard assessment, vulnerability assessment, resilience enhancement strategies, and policy frameworks. Seismic hazard assessment is the first step in understanding the potential risks earthquakes pose to roadway infrastructure. Ground motion prediction models (GMPMs) are absolutely vital in estimating ground shaking intensity and parameters critical for seismic design. Regional GMPMs, tailored to specific seismic activity patterns, enhance the accuracy of hazard assessments, guiding engineers in developing more resilient designs. Vulnerability assessment quantitatively evaluates road system components' response to ground shaking. Fragility curves, vulnerability indices, and damage scenarios offer valuable insights into the seismic performance of roadways. Utilizing real-world data from past earthquakes ensures the accuracy and reliability of vulnerability models. It is of utmost importance to ensure that roadway infrastructure is able to withstand earthquakes, preventing their devastating impact on transportation networks.

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