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Review Article

Advanced Techniques for Earthquake-Resistant Design of Transportation Structures

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ABSTRACT

This paper discusses the importance of earthquake-resistant design in transportation infrastructure, highlighting the need for robust techniques to mitigate damage and ensure user safety. It discusses advanced methodologies and technologies used in seismic design, including site-specific hazards, structural response analysis, innovative retrofitting techniques, and successful implementations of these strategies. The paper also highlights the need for sustainable design in bridge construction, balancing structural integrity with environmental consciousness. It also highlights the significance of disaster-resistant urban transportation systems in bolstering city infrastructure resilience. The paper delves into seismic vulnerability assessment methodologies for highway bridges, offering insights into economic loss estimation, retrofitting decisions, and disaster response planning. The review aims to provide a comprehensive understanding of the challenges and opportunities inherent in earthquake-resistant design within transportation engineering, guiding future research and practical implementations.

Keywords: Seismic Technology, Transportation Engineering, Highway Systems, Sustainable design, Urban Transportation Resilience, Seismic Vulnerability Assessment, Disaster Mitigation

Introduction

Earthquakes can cause catastrophic damage to transportation infrastructure, disrupt supply chains, and endanger public safety.[1] Traditional seismic design practices have evolved over time, incorporating lessons from past earthquakes and engineering knowledge.[2] However, the increasing frequency and severity of seismic events necessitate continuous innovation in earthquake-resistant design techniques. This introduction explores earthquake-resistant design within transportation engineering, highlighting the multifaceted nature of seismic hazards, including earthquake magnitude, frequency, soil conditions, and ground motion characteristics. The historical evolution of seismic technology in transportation engineering emphasises the need for continuous innovation in earthquake-resistant design techniques.[3] Sustainable design principles, including environmental stewardship, resource efficiency, and societal resilience, are crucial in earthquake-resistant transportation infrastructure. By integrating sustainable practices into seismic design, engineers can enhance the longevity and functionality of transportation systems while minimising their ecological footprint and promoting societal well-being.[4] This review paper aims to explore the interplay between seismic hazards and transportation infrastructure, identifying key challenges, innovative solutions, and future research directions in earthquake-resistant design.

Literature Review

This review explores the evolution of seismic technology in transportation engineering, highlighting current deficiencies in highway systems and suggestions for improvement. It emphasises sustainable design considerations in bridge construction to withstand earthquakes while minimising damage and disruption.[5] The article also highlights the importance of earthquake-resistant urban transportation systems in city infrastructure. The review also emphasises the need to evaluate the seismic vulnerability of highway bridges for economic losses, retrofitting decisions, and disaster response planning.[6] It proposes an innovative restraining system for precast concrete I-beam bridges and reviews twin transportation tunnels' responses to earthquake loading (table no. 1).

Table 1.Summary of Papers on Earthquake Resistance and Disaster Mitigation in Transportation Engineering

Paper	Summary	Main findings	Limitations
Review and prospect of earthquake resistance and disaster mitigation technology of highway engineering	The paper provides a review and prospects of earthquake resistance and disaster mitigation technology in highway engineering, highlighting the evolution of seismic technology, current deficiencies in the highway system, and suggesting areas for enhancement.	The paper reviewed the development of seismic technology in highway engineering, identified current deficiencies in the highway system, and suggested future research areas for improvement.	Limitations include deficiencies in the current highway system and suggestions for further research and enhancement.
Sustainable design considerations in the construction of bridges to resist the effects of strong earthquakes	The abstract discusses the evolution of seismic-resistant bridge design towards sustainability, emphasizing the need for bridges to withstand earthquakes while minimizing damage and disruption to traffic flow and the environment, along with ongoing research on innovative technologies.	Bridges designed with modern ductile details and capacity design concepts can withstand inelastic deformation with minimal collapse risk. ductile design approaches may lead to significant permanent displacements of the roadway, impacting post-earthquake traffic flow. recommendations are provided for future research and deployment needs in sustainable bridge design.	The limitations of the study are not explicitly stated, but the need for further research and development in sustainable bridge design is implied.
Earthquake-resistant structures : a low-damage and ductile solution through structural movability and passive energy dissipation	The paper discusses earthquake-resistant structures that allow controlled movement and uplift, utilize slip-friction connectors for energy dissipation, and demonstrate ductile behavior through experimental and numerical studies.	Allowing partial and temporary uplift of structures can be beneficial in reducing seismic forces and inelastic deformations. slip-friction connectors can significantly contribute to reducing induced seismic energy. the combination of timber wall, shear key, and slip-friction connectors can provide a ductile and low damage structural solution.	The study focuses on timber shear walls, limiting generalizability to other types of structures. the research is mainly experimental and numerical, suggesting a need for further real-world application and validation. long-term durability and maintenance requirements of the proposed earthquake-resistant structures are not discussed.

A critical review of the research on the disaster resistant urban transportation system	The paper provides a critical review of research on disaster-resistant urban transportation systems, emphasizing its importance in city infrastructure.	The paper provides a critical review of research on disaster-resistant urban transportation systems and discusses future development in this area.	Not mentioned
A summary of studies on main factors of earthquake resistance of urban ramp bridge	The paper provides a summary of the stress characteristics and factors influencing the seismic performance of ramp bridges in urban areas, discussing the importance of various structural elements and proposing future research directions.	The study summarizes stress characteristics of interchange bridges and typical tunnel bridge damage, discusses factors affecting seismic performance of ramp structures, and proposes future research directions.	The study does not provide a comprehensive analysis of all factors affecting earthquake resistance of urban ramp bridges. future research on seismic performance of bridges is suggested
Seismic vulnerability assessment of rc bridge –a review	The abstract emphasizes the importance of evaluating the seismic vulnerability of highway bridges to assess economic losses, make retrofitting decisions, and plan for disaster response.	Evaluating the seismic vulnerability of highway bridges is crucial for assessing economic losses and making retrofitting decisions. vulnerability assessment of bridges aids in disaster response planning and estimating direct monetary loss.	The limitations of the study are not explicitly stated in the abstract.
Earthquake resistant structures	The abstract provides an overview of earthquakes, their consequences, challenges in creating earthquake-resistant structures, and various design approaches for earthquake resistance.	The study highlights challenges in providing earthquake resistance, proposes ductile design approach, discusses base isolation and energy-dissipating devices, and covers seismic assessment and lifeline resistance.	Not mentioned
A proposal for the improvement of the earthquake resistance of multi-span precast i-beam bridges	The study proposes an innovative restraining system for precast concrete i-beam bridges to improve earthquake resistance, tested on a bridge in greece converted to a ductile system with active seismic stoppers.	The study proposes an innovative restraining system to enhance theX earthquake resistance of precast concrete I-beam bridges, demonstrating effectiveness in reducing seismic movements.	Limited generalizability due to the study being conducted on only one bridge in Greece and the presence of additional seismic stoppers affecting the results

Response of twin transportation tunnel in earthquake loading: a review	Experimental, numerical, analytical methods or a combination of the above techniques are used to design and investigate the stability under static and dynamic conditions.	The paper provides a review and summary of design methods, stability assessment, and various factors influencing twin tunnels, including ground settlement, earthquake response, tunnel spacing, and alignment, offering insights for engineers and researchers in the field.	The study reviewed ground settlement, tunnel response during earthquake loading, and design criteria for twin tunnels based on past literature.
Hybrid simulations for the seismic evaluation of resilient highway bridge systems	The innovative design of the bridge bent columns demonstrated superior seismic performance.	The paper discusses the seismic evaluation of resilient highway bridge systems, focusing on maintaining functionality post-seismic events, utilizing innovative connecting devices like the v-connector, and incorporating self-centering mechanisms for resiliency.	The v-connector system improved seismic behavior by protecting bridge columns, while the bridge bent with self-centering columns demonstrated superior seismic response with minimal damage and residual drifts.

Table 2.Seismic design considerations

Description	Details	Analysis Method	Design Considerations	Performance Objectives
Regional Seismic Hazards	The study of earthquake ground motions at a specific site, considering factors like: • Magnitude of potential earthquakes • Frequency of earthquake occurrence • Local soil conditions (amplifications or reductions) • Ground motion characteristics (peak ground acceleration, spectral content)	• Historical earthquake data analysis • Seismic hazard maps review • Geologic investigations (fault lines, soil types)	• Site selection (avoiding faults or soft soils) • Foundation design (consideration of soil capacity and liquefaction potential)	• data gathering for further analysis
Seismic Hazard Analysis	Quantifies the probability of exceeding specific ground motion levels at a site within a given timeframe. • PSHA (Probabilistic Seismic Hazard Analysis) • Ground Response Analysis	• PSHA uses statistical models and earthquake catalogs to estimate earthquake return periods. • Ground response analysis uses sophisticated software and requires detailed soil data to assess site-specific ground motion.	• Design earthquake selection (characteristic earthquake with specific return period) • Derivation of seismic loads for structural analysis	• Provides quantitative data on earthquake shaking intensity for design purposes

Structural Response Analysis	Evaluates the dynamic behavior of a structure under simulated earthquake loads. • Computer simulations • Shake table testing	• Finite element analysis software for complex structural models. • Shake table testing requires specialized facilities and scaled-down physical models.	• Structural configuration and materials selection (considering strength, ductility, and energy dissipation) • Determination of member capacities (beams, columns, connections)	• Evaluates a structure's strength, stiffness, and potential failure modes under earthquake loading.
Design Approach	Sets predefined performance objectives for a structure during an earthquake, ensuring it meets specific criteria. • Performance-based design	• Life-cycle costing analysis (considering construction, maintenance, and potential repair costs) • Stakeholder input (e.g., owner's priorities, building function)	• Building code compliance (adherence to minimum safety requirements) • Sustainability considerations (using environmentally friendly materials and practices)	- Achieves a balance between safety, functionality, and cost-effectiveness for the specific structure.
Performance Objectives	• Limit structural damage to a repairable level (minimizing downtime and repair costs) • Ensure life safety by preventing collapse during an earthquake • Maintain functionality for critical structures (hospitals, bridges) to ensure post-earthquake operation	• Objectives may vary based on building occupancy type (residential vs. commercial) • Recovery time objectives (how quickly a building needs to be operational after an earthquake)	• Prioritizes objectives based on building importance and its potential societal impact in case of failure.	-

Seismic Design Considerations

Effective seismic design begins with a thorough understanding of regional seismic hazards, including the magnitude and frequency of potential earthquakes, soil conditions, and ground motion characteristics.[7] Engineers employ probabilistic seismic hazard analysis (PSHA) and ground response analysis to quantify these hazards and inform design parameters.[8] Structural response analysis, conducted through computer simulations and shake table testing, evaluates the dynamic behaviour of transportation structures under seismic loading (table no. 2). Performance-based design approaches focus on achieving predefined performance objectives, such as limiting structural damage and ensuring post-earthquake functionality.[9]

Innovative Retrofitting Techniques

Retrofitting existing transportation structures is a critical aspect of seismic risk mitigation, especially in regions with ageing infrastructure.[10] Engineers utilise a variety of retrofitting techniques to strengthen vulnerable elements and improve overall seismic performance.[11] Common retrofit strategies include the addition of supplementary damping devices, the installation of seismic isolation bearings, and the reinforcement of structural members with fibre-reinforced polymers (FRP) or steel elements .[12] These techniques enhance the ductility, energy dissipation capacity, and resilience of transportation structures, allowing them to withstand seismic forces without compromising safety or functionality.[13]

Applications

Several practical applications showcase the application of advanced earthquake-resistant design techniques in transportation projects around the world. Examples include the retrofitting of the San Francisco-Oakland Bay Bridge following the 1989 Loma Prieta earthquake[14], the seismic isolation of the Kobe-Osaka highway in Japan[15], and the use of base isolation systems in the construction of the Istanbul Strait Road Tube Crossing in Turkey.[16] These projects demonstrate the effectiveness of innovative seismic design approaches in minimising damage and ensuring the continued operation of critical transportation infrastructure during and after seismic events.[17]

AI in Earthquake-Resistant Design: Advancements and Limitations

The integration of artificial intelligence (AI) in earthquake-resistant design has shown significant potential for improving the accuracy and efficiency of structural analysis, design, and monitoring. AI algorithms can analyse massive amounts of seismic data, identify damage locations after an earthquake, and design structural control systems. AI-based methods use machine learning techniques to make fast and reliable predictions about earthquakes, enabling engineers to design more robust and resilient structures. The integration of artificial intelligence (AI) in earthquake-resistant design has shown significant potential for improving the accuracy and efficiency of structural analysis, design, and monitoring. AI algorithms can analyse massive amounts of seismic data, identify damage locations after an earthquake, and design structural control systems. AI-based methods use machine learning techniques to make fast and reliable predictions about earthquakes, enabling engineers to design more robust and resilient structures.

The use of AI in earthquake-resistant design can lead to benefits such as improved efficiency, productivity, knowledge, reduced errors, enhanced collaboration, and improved accuracy. AI can automate tedious tasks, improve project duration estimation, and help engineers focus on more creative and strategic tasks. Additionally, AI can maximise the efficacy and efficiency of materials, reducing costs and improving sustainability in the construction industry.

However, AI cannot replace human expertise in creative problem-solving, interpretation of drawings, model checking, site surveying, and improvisation. Instead, AI complements engineers' skills by automating time-consuming tasks, providing data-driven insights, and expanding possibilities for innovative and efficient structural solutions.

In conclusion, the integration of AI in the earthquake-resistant design of transportation structures can lead to significant improvements in the accuracy and efficiency of structural analysis, design, and monitoring. However, AI cannot replace human expertise, and there are limitations to its use in structural engineering.[18,22]

Conclusion

The seismic resilience of transportation infrastructure is crucial to mitigating the destructive impacts of earthquakes. Advanced techniques for earthquake-resistant design can enhance the safety and functionality of transportation structures in seismic regions. Effective seismic design involves understanding regional seismic hazards, using probabilistic seismic hazard analysis (PSHA) and ground response analysis, and evaluating structural response through computer simulations and shake table testing. Performance-based design approaches aim to limit structural damage and ensure post-earthquake functionality.

Innovative retrofitting techniques are essential for seismic risk mitigation, employing techniques like supplementary damping devices, seismic isolation bearings, and reinforcement with fiber-reinforced polymers (FRP) or steel elements. Case studies demonstrate the effectiveness of these strategies in minimising damage and ensuring continued operation post-earthquake.

Practical applications of advanced earthquake-resistant design techniques in transportation projects worldwide include retrofitting the San Francisco-Oakland Bay Bridge, seismic isolation of the Kobe-Osaka highway, and base isolation systems in the Istanbul Strait Road Tube Crossing. Continued research and development are essential to address emerging challenges and ensure the long-term sustainability and safety of transportation systems in seismic regions.

References

1. Kumar S, Havey T. Before and after disaster strikes: A relief supply chain decision support framework. International Journal of Production Economics. 2013 Oct 1;145(2):613-29.
2. Chandler AM, Lam NT. Performance-based design in earthquake engineering: a multi-disciplinary review. Engineering structures. 2001 Dec 1;23(12):1525-43.
3. Smith KG. Innovation in earthquake resistant concrete structure design philosophies; a century of progress since Hennebique's patent. Engineering structures. 2001 Jan 1;23(1):72-81.

4. Basu D, Misra A, Puppala AJ. Sustainability and geotechnical engineering: perspectives and review. Canadian geotechnical journal. 2015;52(1):96-113.
5. Mahin S. Sustainable design considerations in earthquake engineering. InThe 14th world conference on earthquake engineering 2008 (Vol. 8).
6. Li Y, Dong Y, Frangopol DM, Gautam D. Long-term resilience and loss assessment of highway bridges under multiple natural hazards. Structure and Infrastructure Engineering. 2020 Apr 2;16(4):626-41.
7. Douglas J, Edwards B. Recent and future developments in earthquake ground motion estimation. Earth-Science Reviews. 2016 Sep 1;160:203-19.
8. Li B, Cai Z, Xie WC, Pandey M. Probabilistic seismic hazard analysis considering site-specific soil effects. Soil Dynamics and Earthquake Engineering. 2018 Feb 1;105:103-13.
9. Cook DT. Advancing performance-based earthquake engineering for modern resilience objectives (Doctoral dissertation, University of Colorado at Boulder).
10. Alipour A, Shafei B. Seismic resilience of transportation networks with deteriorating components. Journal of Structural Engineering. 2016 Aug 1;142(8):C4015015.
11. Lourenço PB, Ciocci MP, Greco F, Karanikoloudis G, Cancino C, Torrealva D, Wong K. Traditional techniques for the rehabilitation and protection of historic earthen structures: The seismic retrofitting project. International Journal of Architectural Heritage. 2019 Jan 2;13(1):15-32.
12. Kiakojouri F, De Biagi V, Chiaia B, Sheidaii MR. Strengthening and retrofitting techniques to mitigate progressive collapse: A critical review and future research agenda. Engineering structures. 2022 Jul 1;262:114274.
13. Benoy, Sneha, A. R. Vijayanarayanan, and M. Saravanan. "Paradigm shift to resilience based design for improved seismic behaviour–State-of-the-Art." Materials Today: Proceedings (2023).
14. Chakos, A., & Zoback, M. L. "California's San Francisco Bay Area: An Epicenter of Community Resilience." *The Disaster Resilience Challenge: Transforming Theory to Action*, 2018, pp. 211.
15. Nojima N, Kato H. Functional Damage and Recovery of Highway Networks in Major Earthquake Disasters in Japan. InLifelines 2022 2022 (pp. 154-165).
16. Memisoglu Apaydin N, Zulfikar AC, Cetindemir O. Structural health monitoring systems of long-span bridges in Turkey and lessons learned from experienced extreme events. Journal of Civil Structural Health Monitoring. 2022 Dec;12(6):1375-412.
17. Shadabfar M, Mahsuli M, Zhang Y, Xue Y, Ayyub BM, Huang H, Medina RA. Resilience-based design of infrastructure: Review of models, methodologies, and computational tools. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering. 2022 Mar 1;8(1):03121004.
18. Akhai, Shalom. "Towards Trustworthy and Reliable AI The Next Frontier." Explainable Artificial Intelligence (XAI) in Healthcare 1 (2024): 119-129.
19. Akhai S, Kumar V. Quantum Resilience and Distributed Trust: The Promise of Blockchain and Quantum Computing in Defense. InSustainable Security Practices Using Blockchain, Quantum and Post-Quantum Technologies for Real Time Applications 2024 Apr 3 (pp. 125-153). Singapore: Springer Nature Singapore.
20. Srivastava H, Akhai S. The smart tapping identification model without installing a control program in modern wireless communication. In2022 International Interdisciplinary Humanitarian Conference for Sustainability (IIHC) 2022 Nov 18 (pp. 159-164). IEEE.
21. Akhai S, Balu V. Code Injection Assault & Mitigation Model to Prevent Attacks. In2022 11th International Conference on System Modeling & Advancement in Research Trends (SMART) 2022 Dec 16 (pp. 1324-1328). IEEE.
22. Akhai, Shalom. "Navigating the Potential Applications and Challenges of Intelligent and Sustainable Manufacturing for a Greener Future." (2023): 2237-2243.