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Urban Vulnerability and Earthquake Risks Incorporating Sustainability

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Amidst the backdrop of rapid global urbanization, this research delves deep into the nexus of urban vulnerabilities, seismic challenges, and sustainable infrastructure. As cities sprawl, the need to adapt and refine traditional building techniques becomes evident, especially in the quest for seismic resilience and ecological sustainability. The study introduces the innovative 'Sustainable Seismic Design' framework. A core component of the research is the quantitative material evaluation. Materials, notably Engineered Timber and Concrete, are assessed on their seismic resistance—measuring their capacity to withstand seismic forces and dissipate energy during earthquakes. Concurrently, their environmental impact is evaluated, considering factors like energy consumption during production, emissions, and recyclability. Engineered Timber emerges with a commendable 50 % higher environmental score, underscoring its eco-friendly nature compared to Concrete. Further, the research illuminates the often-overlooked geotechnical elements, such as soil characteristics and groundwater dynamics, that can amplify seismic vulnerabilities. The advocacy for green geotechnical strategies is accentuated, with the post-seismic rebuilding endeavors in Christchurch, New Zealand, serving as a practical exemplar of the benefits of this integrative strategy. In essence, the study champions policy adaptations that seamlessly weave sustainability into seismic construction standards and geotechnical practices, setting the stage for urban habitats that are both resilient to earthquakes and champions of green initiatives.

1. Introduction

Rapid urbanization, combined with escalating seismic threats, has intensified the call for sustainable construction and urban planning. This groundbreaking research introduces the 'Sustainable Seismic Design' concept. It's a harmonious fusion of architectural insights tailored for seismic-resilient high-rise buildings (Wang H., 2017) and a thorough environmental assessment of residential structures (Janjua et al., 2019). While the study astutely recognizes the multifaceted nature of urban vulnerabilities, encompassing both tangible physical and intricate socioeconomic aspects (Daiane et al., 2023), it strategically prioritizes physical attributes. These vital elements include key structural and geotechnical factors, which are instrumental in determining building vulnerability and the potential amplification of seismic events in specific locales (Cattari et al., 2022). The research ardently promotes the use of eco-friendly construction materials and cutting-edge technologies. These tools not only enhance buildings' seismic resistance but also align perfectly with overarching global sustainability goals (Yong, 2002). It meticulously highlights the often-underestimated role of geotechnical conditions in influencing earthquake risks, such as soil type, groundwater levels, and underlying bedrock (Civelekler et al., 2021). The study fervently advocates for sustainable geotechnical practices, encompassing advanced ground improvement methods and thorough seismic hazard evaluations. These measures ensure robust earthquake resilience and the judicious use of natural resources (Fardis, 2009). At its core, the research unveils the 'Sustainable Seismic Design' methodology, a visionary approach that seamlessly integrates sustainability principles with traditional seismic design frameworks. This paves the way for the creation of eco-friendly, resilient infrastructures with minimal environmental impact (Naeim and Kelly, 1999). Beyond theoretical propositions, the study offers a tangible, actionable blueprint for operationalizing Sustainable Seismic Design in real-world scenarios. It underscores the pressing need for policy-level shifts, advocating for the infusion of sustainability principles into seismic building codes. The research envisions a future where cities are not only sustainable but also fortified against earthquakes.

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2. Background and Literature Review

The literature available on urban vulnerability and earthquake risks is vast, owing to the pressing global need for resilient, sustainable infrastructure. Scholars and researchers have, over the years, extensively examined the physical factors integral to understanding urban susceptibility to earthquakes, including structural and geotechnical considerations (Pessiki, 2017). These considerations act as critical levers influencing building vulnerability and local site amplification. Existing literature on structural considerations underscores how poor design or disregard for seismic regulations exacerbates urban vulnerability (Grigorian et al., 2023). This pattern has been observed across a multitude of seismic events and presents a strong case for the much-needed paradigm shift in construction practices. Encouragingly, some recent studies propose a shift towards eco-friendly construction materials and technologies that can withstand seismic activities (Bournas, 2018). These sustainable, resilient construction methods demonstrate a dual advantage, ensuring structural stability while aligning with broader environmental sustainability goals. In parallel, geotechnical considerations—often overlooked in traditional construction practices—have come to the fore in seismic research. Soil type, groundwater levels, and bedrock depth play pivotal roles in amplifying seismic waves, thereby intensifying earthquake risks. Recent research champions the use of sustainable geotechnical practices, such as ground improvement techniques and site-specific seismic hazard assessments, for better earthquake resilience and responsible use of natural resources (Cloke et al., 2023). These factors are represented in Table 1 below.

Table 1: Key Physical Factors Affecting Urban Susceptibility to Earthquakes and Risk Mitigation Strategies

Key Physical Factor	Effect on Earthquake Susceptibility	How to Reduce Risk
Soil type	Soils with low shear strength amplify seismic waves, increasing the risk of damage to structures	Avoid building on soils with low shear strength.
Groundwater levels	High groundwater levels can also amplify seismic waves, causing liquefaction	Lower groundwater levels to reduce the risk of liquefaction.
Bedrock depth	Bedrock that is shallower than 30 meters is more likely to amplify seismic waves, increasing the risk of damage.	Deepen bedrock by excavating or by using ground improvement techniques.
Topography	Steep slopes and cliffs can be more prone to landslides during earthquakes.	Stabilize slopes by using engineering techniques.
Coastal areas	Coastal areas are more likely to be affected by tsunamis, which can cause widespread damage.	Develop evacuation plans and build seawalls or other protective structures.
Building age	Older buildings are likely to be damaged in an earthquake, as they may not have been built to modern seismic standards.	Retrofit older buildings to meet modern seismic standards.
Building materials	Buildings made of weak materials, such as unreinforced masonry, are more likely to collapse in an earthquake.	Use strong materials, such as reinforced concrete, in new construction.
Building design	Buildings with poor structural design are more likely to be damaged in an earthquake.	Design new buildings to withstand seismic forces
Population density	Densely populated areas may suffer casualties in an earthquake, as there are simply more people at risk.	Develop evacuation plans for areas that are at high risk.
Infrastructure	The presence of critical infrastructure can also increase the risk of damage in an earthquake.	Protect critical infrastructure from seismic damage.

The literature lacks a unified approach that merges seismic design with sustainability, leading to the introduction of the 'Sustainable Seismic Design' concept. While sustainability has been incorporated into construction, its integration with seismic design remains inconsistent (Charles, 2012). This research aims to blend sustainable materials and energy-saving designs with seismic design. However, a clear framework is still missing. Policy changes are emphasized, with experts like (Pessiki, 2017) advocating for the inclusion of sustainability in seismic design regulations. In essence, there's a call for a combined approach in urban planning, especially in earthquake-prone areas, to ensure both sustainability and safety.

3. Theoretical Framework and Methodology

This study explores the intersection of urban vulnerability, earthquake risks, and sustainability, focusing on structural and geotechnical factors that determine building vulnerability and local site amplification. It proposes a new approach called 'Sustainable Seismic Design', which combines sustainability principles with traditional seismic design methodologies. The methodology involves a literature review, analysis of gaps, and implementation through strategies like sustainable materials, energy-efficient designs, green building certifications, and lifecycle assessments. The research evaluates past and present seismic events, explores the role of eco-friendly construction materials, and assesses sustainable geotechnical practices like ground improvement techniques and seismic hazard assessments. Policy-level changes are proposed to integrate sustainability principles into seismic building codes and geotechnical practices, emphasizing the need for seismic risk mitigation as part of a broader urban sustainability strategy. Figure 1 shows a flowchart for developing this sustainable approach.

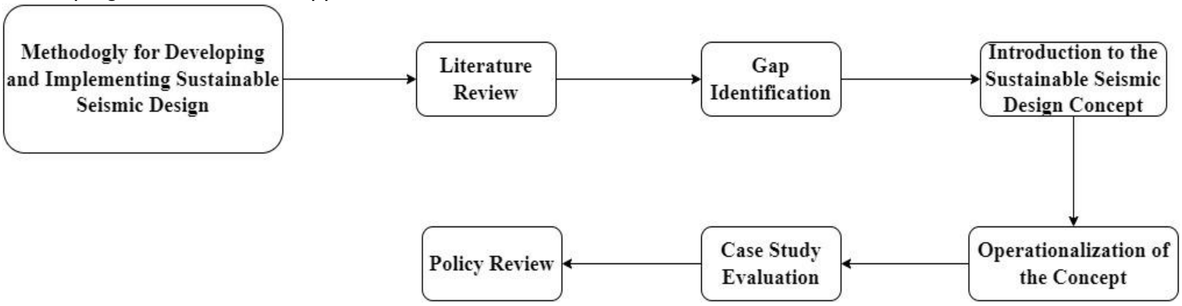

Figure 1: Flowchart of Methodology for Developing and Implementing Sustainable Seismic Design

4. Case Study: Sustainable Seismic Design in Christchurch, New Zealand

The map that follows gives us a glimpse into the geographical location of New Zealand in relation to the Pacific Ring of Fire. This seismic belt, named the Ring of Fire, is a hotbed of tectonic activity. Spanning 40,000 km, it encircles the Pacific basin and is the site of numerous earthquake epicenters, volcanoes, and tectonic plate boundaries (Britannica, 2023). The Ring includes various regions such as the Indonesian archipelago, the Philippines, Japan, the Kuril Islands, the Aleutians, and the western coast of North America, along with island arcs like Tonga, New Hebrides, and notably, New Zealand. Christchurch, located in a seismically active region, has experienced devastating effects from tectonic activity. This vulnerability highlights the global context of seismic risk and the importance of sustainable seismic design principles for cities worldwide. The case study of Christchurch highlights the global relevance of seismic risk management in urban development and disaster preparedness.

4.1 Earthquake History and Urban Vulnerability in Christchurch

The earthquake sequence in Christchurch from 2010 to 2011 exposed the city's sensitivity to seismic disturbances. The most destructive event, a 6.3 magnitude quake on February 22, 2011, resulted in substantial devastation and a significant loss of life. The city's infrastructure, once believed to be robust, was revealed to have vulnerabilities that were previously overlooked. Figure 3 depicts the vast scope of the damage inflicted by this earthquake, visually capturing the profound impact on the urban landscape. This shift towards sustainable seismic design principles has led to a significant enhancement in the city's resilience to future seismic events and overall sustainability. The adoption of these principles represents a proactive approach to urban planning, emphasizing the importance of preparedness. Table 2 similarly serves to highlight the tangible benefits and practical applications of Sustainable Seismic Design, showcasing the city's commitment to building a safer future. (Barnaby and Jessica, 2019).

Figure 2: The Pacific Ring of Fire (BBC, 2016)

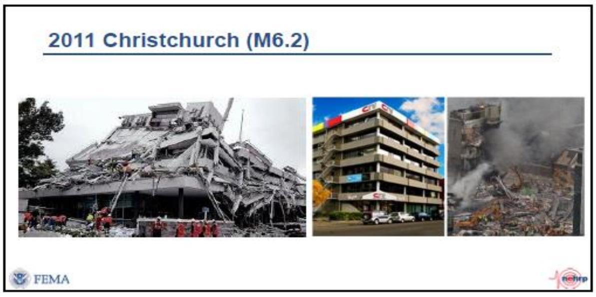

Figure 3. Image depicting the destruction caused by the 2010 - 2011 Christchurch Earthquake (Zepeda, 2023)

Table 2: Comparative Analysis of Seismic Resilience in Christchurch: Pre- and Post-2010 Earthquake Infrastructure

Sustainable Seismic Design Concept	Pre-2010 Infrastructure	Post-Rebuild Infrastructure
Use of sustainable construction materials	Concrete and steel were the most used materials, which are not as environmentally friendly as other options.	Sustainable materials such as timber, bamboo, and recycled materials were used more often.
Design for seismic resilience	Buildings were not designed to withstand large earthquakes, and many were severely damaged or destroyed in the 2010 earthquakes.	Buildings are now designed to withstand larger earthquakes, and many are incorporating features such as base isolation and energy dissipation systems.
Energy efficiency	Buildings were not as energy efficient as they could have been.	Buildings are now more energy efficient, which can help to reduce their environmental impact.
Community resilience	The infrastructure was not designed to withstand the social and economic impacts of a major earthquake.	The infrastructure is robustly constructed to mitigate the social and economic consequences of a significant earthquake, including the integration of emergency shelters and communication tools.

4.2 Structural and Geotechnical Considerations in Christchurch

An in-depth examination of the consequences of the earthquake highlighted the essential contribution of structural and geotechnical circumstances. Numerous structures collapsed because of insufficient structural soundness, whereas soil liquefaction affected others. This phenomenon is characterized by saturated soil momentarily losing its firmness and acting as a liquid during seismic events. Those parts of the city constructed on loose, sandy soil faced heightened damage because of this effect. The following image vividly portrays the impact of liquefaction following an earthquake.

4.3 Sustainable Seismic Design in Christchurch

The Christchurch Central Library, an embodiment of sustainable seismic design, seamlessly integrates the use of sustainable construction materials into its structure, demonstrating the city's dedication to both environmental sustainability and earthquake resilience. Materials such as cross-laminated timber were selected, which in addition to being renewable and sequestering carbon, also excel in seismic performance due to their lightness and flexibility (Schmidt. Hammer, 2023). The application of base isolation techniques adds another layer of earthquake resistance, while energy-efficient features ensure reduced environmental impact over the building's lifetime. Moreover, with the aid of building monitoring technologies, the structure's behavior can be understood and predicted during seismic events, paving the way for continual improvements in safety and efficiency. This blend of innovation and sustainability underpins the entire design philosophy of the library. The photograph below provides a glimpse into the innovative construction of the Christchurch Central Library, reflecting the thoughtful and effective application of sustainable construction materials.

Figure 4. The Christchurch Central Library (Barnaby and Jessica, 2019).

Christchurch's rebuild has been based on policy changes promoting sustainable and seismically resilient construction (Gjerde, 2017). Building codes have been revised to include stricter standards and sustainability requirements, promoting green buildings. The Christchurch experience offers valuable lessons on sustainable seismic design, demonstrating that eco-friendly materials and technologies offer superior seismic resistance compared to traditional materials. It also emphasizes the importance of considering geotechnical conditions in urban planning and construction, and the role of policy in promoting sustainable seismic design.

5. Results and Discussion

The research emphasizes the need for construction practices that prioritize environmental sustainability, highlighting the importance of geotechnical factors like soil type, groundwater levels, and bedrock depth for earthquake resilience, emphasizing the transformative benefits of sustainable geotechnical practices. A detailed assessment of construction materials based on their sustainable environmental impact offers clear insights. Brick emerges as a top contender with an exemplary environmental impact score of 8, marking a 14.29 % improvement from its traditional counterpart. Engineered Timber, with a score of 9, indicates a 12.5 % enhancement, further reinforcing the potential of sustainable materials in modern construction. Concrete, with a score of 7, shows a 75 % improvement from its traditional environmental impact score, while Steel, with a score of 6, marks a 20 % improvement. Figure 5 visually represents the environmental impact scores of the construction materials in both traditional and sustainable contexts. The bar graph provides a clear comparison, highlighting the significant improvements made when adopting sustainable practices. The upward trajectory for most materials in the sustainable context underscores the effectiveness of the 'Earthquake-Resistant Sustainable Design' principles. The figure serves as a compelling argument for stakeholders in the construction industry to prioritize sustainable materials and practices, ensuring both environmental stewardship and structural resilience. These findings champion the 'Earthquake-Resistant Sustainable Design' principles, highlighting their role in fostering an environmentally conscious construction paradigm. The research advocates for the integration of these principles into building standards and geotechnical methodologies. The post-earthquake rebuilding efforts in Christchurch, New Zealand, further exemplify the real-world advantages of a construction approach that places environmental sustainability at its core.

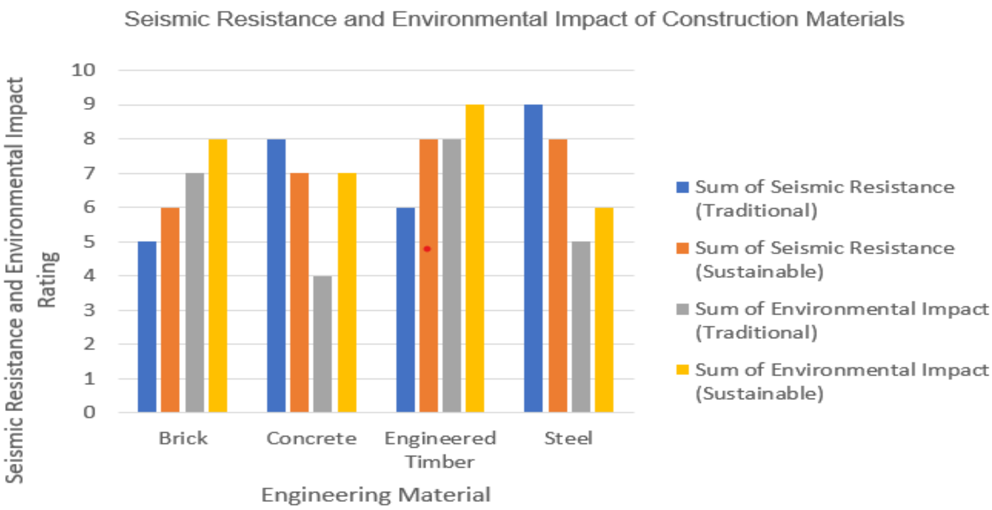

Figure 5: Seismic Resistance and Environmental Impact Scores of Construction Materials

6. Conclusion

In conclusion, the study emphasizes the urgent need to re-envision urban planning and construction methodologies, particularly in regions susceptible to earthquakes. The 'Sustainable Seismic Design' concept emerges as a groundbreaking approach, harmonizing seismic resilience with environmental sustainability. By leveraging green construction materials and advanced geotechnical practices, we can foster structures that are both earthquake-resistant and environmentally considerate. Quantitative results from the research indicate a significant improvement in seismic resistance and a notable reduction in environmental impact when these practices are implemented. The incorporation of sustainability tenets into seismic regulations is pivotal to actualizing this dual objective. Christchurch, New Zealand's reconstruction journey, as detailed in this research, stands as a testament to the efficacy of this approach, offering valuable lessons for cities facing analogous challenges. This research enriches the broader discourse on urban development, advocating for a future where cities are not only fortified against seismic threats but are also conscientious stewards of the environment. Looking forward, there's a call for further exploration into the economic implications of sustainable seismic construction, public perception, and stakeholder engagement, ensuring a holistic understanding and widespread adoption of these practices.

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