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Geotechnical Innovations for Seismic-Resistant Urban Infrastructure

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ABSTRACT

As urban areas continue to expand into seismically active regions, the imperative for developing earthquake-resistant infrastructure has never been greater. This paper presents a comprehensive examination of innovative geotechnical engineering solutions aimed at enhancing the resilience of urban infrastructure against seismic threats. It explores cutting-edge approaches including advanced base isolation techniques, soil liquefaction mitigation strategies, and the incorporation of shape memory alloys (SMAs) in foundation systems. Through detailed case studies, such as the Tokyo Skytree, Christchurch's soil stabilization projects, and the San Francisco Bay Bridge retrofit, the effectiveness, adaptability, and sustainability of these solutions are demonstrated. The paper conducts a comparative analysis of these technologies based on cost, implementation feasibility, and seismic mitigation effectiveness, and assesses their sustainability in the context of urban development. Despite facing challenges such as high initial costs and the need for specialized expertise, the potential of these technologies to significantly improve the safety and sustainability of urban environments is clear. The study concludes with a call for continued innovation, interdisciplinary collaboration, and proactive policymaking to foster the widespread adoption of these critical advancements. This research not only contributes to the academic field but also provides practical insights for engineers, urban planners, and policymakers striving to build more resilient cities in the face of increasing seismic risks.

Keywords: Earthquake-Resistant Design, Geotechnical Engineering, Urban Resilience, Soil Liquefaction, Base Isolation Techniques, Shape Memory Alloys

INTRODUCTION

In recent decades, the escalating frequency and severity of seismic events have starkly highlighted the critical need for resilient urban infrastructure that can withstand earthquakes. Globally, urban centers are proliferating, often in seismically active zones, escalating the risk of significant human and economic losses during seismic disturbances (Šipoš et al., 2017; Ademović, 2023). The resilience of urban infrastructure to seismic activities not only safeguards lives and minimizes damage but also ensures rapid recovery and the continuity of essential services after disasters. Thus, enhancing earthquake resilience transcends engineering challenges and becomes a societal imperative, closely aligned with sustainable development goals aimed at fostering cities that are inclusive, safe, resilient, and sustainable (Hák et al., 2016).

This paper explores innovative geotechnical engineering solutions that augment the earthquake resistance of urban infrastructure. While traditional approaches have concentrated on strengthening structures and enhancing material properties, recent advancements have introduced new paradigms in design and implementation (Fardis, 2022). Specifically, this research delves into cutting-edge technologies such as base isolation techniques, soil liquefaction mitigation strategies, and the application of shape memory alloys (SMAs) in foundation design. Each of these solutions offers a distinct approach to mitigating the impacts of seismic forces, marking a shift towards not merely surviving but thriving in the face of such natural adversities. The paper will provide a detailed review of recent advancements, evaluate their effectiveness through case studies, and discuss their sustainability and integration into current geotechnical practices (Losanno et al., 2021; Kirkwood & Dashti, 2018).

In conducting this investigation, the paper draws upon a diverse array of sources and studies, integrating theoretical frameworks with empirical data to present a comprehensive overview of the state-of-the-art in earthquake-resistant geotechnical engineering. By addressing the technical, economic, and environmental aspects of these innovative solutions, this research aims to make a significant contribution to the discourse on urban resilience, providing actionable insights and directions for future research and implementation (Chang and Araki, 2016; De Luca and Guidi, 2019).

Through this exploration, the paper seeks to inspire continued innovation and adoption of advanced geotechnical methods, ultimately contributing to the broader goal of achieving more resilient urban environments in the context of escalating seismic risks.

Background

Earthquakes present a complex threat to infrastructure, manifesting primarily through ground shaking, surface rupture, soil liquefaction, and ground displacement. The resilience of urban infrastructure against these seismic forces largely hinges on the ground conditions and the engineering strategies employed (Eliau and Rouainia, 2022). Ground shaking, the most immediate and noticeable impact of an earthquake, tests the structural integrity of buildings and bridges by imposing dynamic loads that significantly exceed their designed static capacities. Surface rupture occurs when an earthquake displaces the earth along a fault line, directly shearing and deforming structures in its path. Soil liquefaction, a critical concern in geotechnical engineering, transforms solid soil into a fluid-like state, undermining foundation support and often leading to catastrophic structural failures (Sitharam and Kolathayar, 2018). Lastly, ground displacement can result in the uneven settling or sliding of the ground, potentially causing buildings to tilt or collapse.

Understanding these phenomena is crucial for developing effective seismic mitigation strategies. Advances in geotechnical engineering have deepened our understanding of soil-structure interaction and the behavior of various materials under seismic loads, enabling the development of more resilient design approaches (Salami et al., 2020).

Historically, geotechnical earthquake engineering has focused on enhancing the strength and ductility of structures to better withstand seismic forces. Traditional methods include the use of deep foundation systems for improved anchoring, soil stabilization techniques to prevent liquefaction, and the retrofitting of older structures with reinforcements to enhance their load-bearing capacities (Ghafoori et al., 2022).

Among the cornerstone technologies in earthquake-resistant design is base isolation, which involves constructing a building or structure on flexible bearings rather than directly on the ground. This technique allows the building to move somewhat independently of the ground's movements, significantly reducing the seismic forces transmitted through the structure (Sheikh et al., 2022). Another conventional method involves the use of damping systems, which absorb and dissipate the energy released during an earthquake, thereby reducing the motion of the building and protecting its structural integrity (Yenidogan, 2021). Furthermore, with advancements in computational capabilities, numerical modeling and simulation have become indispensable tools in predicting and analyzing the behavior of geotechnical systems under seismic loading, leading to safer and more precise designs (Firoozi et al., 2023).

A) Advances in geotechnical solutions

The field of geotechnical engineering has witnessed significant advancements aimed at enhancing the earthquake resilience of urban infrastructure. Driven by the urgent need for more effective seismic protection, these innovations employ novel materials, techniques, and technologies that significantly bolster the structural capacity to withstand earthquake forces. This section explores three key areas of recent advancements: base isolation techniques, soil liquefaction mitigation, and the utilization of shape memory alloys in foundations. Each of these approaches represents a significant leap forward in our capacity to design and construct safer urban environments in seismically active areas. By integrating these cutting-edge solutions, engineers and researchers are setting new benchmarks in earthquake-resistant construction, paving the way towards minimizing seismic risks and enhancing the sustainability of urban developments. The following subsections detail the mechanics, applications, and impacts of these groundbreaking advancements in geotechnical engineering.

B) Base isolation techniques

Base isolation is one of the most effective techniques for protecting structures against earthquakes. It involves decoupling a building or structure from the ground, allowing it to move independently of the earth’s movements. Recent developments in base isolation technology have focused on enhancing the materials used and the overall system designs to improve their adaptability and effectiveness in a broader range of seismic scenarios. Innovative materials such as high-damping rubber and layered lead-rubber bearings have shown significant promise in increasing energy absorption capabilities, thereby reducing the transmitted forces during an earthquake (Beirami Shahabi et al., 2020).

Additionally, the integration of smart technology with traditional base isolation systems has led to the development of adaptive base isolation systems. These systems utilize sensors and actuators to modify the structural response in real-time, optimizing the building’s behavior based on the characteristics of the earthquake (Nanda et al., 2016). Such advancements not only enhance the protective functions but also extend the lifespan and operational reliability of these systems under varying seismic conditions.

Equation 1 provides the formula for calculating the energy dissipated by seismic isolation systems during an earthquake. This equation is fundamental in assessing the effectiveness of new materials, such as high-damping rubber and shape memory alloys, which are designed to absorb and dissipate the kinetic energy generated by seismic forces.

$$E_d = \frac{1}{2} k\Delta x^2 \quad (1)$$

where:

- E_d = Energy dissipated (Joules)
- k = Stiffness of the isolation system (Newtons per meter)
- Δx = Displacement amplitude (meters)

Table 1 provides a comparative analysis of traditional and advanced base isolation materials. It highlights differences in energy absorption efficiency, initial cost, lifespan, and maintenance requirements, illustrating the advancements in material science that enhance the performance and cost-effectiveness of modern base isolation systems.

Soil liquefaction mitigation

Soil liquefaction presents a formidable challenge in earthquake engineering. Recent advancements in mitigation techniques include the use of ground improvement methods such as vibro-compaction, which densifies loose sandy soils, and the injection of stabilizing agents to increase soil cohesion. Another innovative approach is the use of microbial-induced calcite precipitation (MICP), a bio-geotechnical method that enhances soil strength through biological processes (Lai et al., 2021).

Each of these methods has its benefits and applications, tailored to specific site conditions and seismic requirements. For example, vibro-compaction is highly effective in sites with uniform sandy layers, while MICP offers an environmentally friendly alternative with the potential for broader application in various soil types. The ongoing development and refinement of these techniques are crucial for their wider adoption and effectiveness in real-world scenarios.

Equation 2 presents the formula used to evaluate the efficiency of soil stabilization methods. This formula calculates the percentage increase in soil shear strength resulting from various stabilization techniques such as deep soil mixing, vibro-compaction, and microbial-induced calcite precipitation. The equation underscores the effectiveness of these methods in enhancing the mechanical properties of soil to withstand seismic forces.

$$Efficiency(\%) = (\frac{\tau_a}{\tau_f} - 1) \times 100 \quad (2)$$

where:

- $\tau_a =$ Shear strength of the soil after applying stabilization techniques (kPa)
- $\tau_f =$ Original shear strength of the soil before treatment (kPa)

Table 2 outlines a comparison of various soil liquefaction mitigation techniques, including vibro-compaction, deep soil mixing, and microbial-induced calcite precipitation (MICP). The table assesses each technique based on cost, effectiveness, environmental impact, and suitability for different soil types, providing essential insights for selecting appropriate methods for specific site conditions.

Table 1. Comparison of traditional vs. advanced base isolation materials

Material Type	Energy absorption efficiency	Initial cost	Lifespan	Maintenance requirements
Plain Rubber Bearings	Moderate	Low	10-15 years	High
High-Damping Rubber	High	Medium	20-30 years	Moderate
Lead-Rubber Bearings	Very High	High	25-35 years	Low

Table 2. Soil liquefaction mitigation techniques and their applicability

Technique	Cost	Effectiveness	Environmental Impact	Soil Type Suitability
Vibro-Compaction	Moderate	High	Moderate	Sandy soils
Deep Soil Mixing	High	Very High	Moderate	Clay and sandy soils
Microbial-Induced Calcite Precipitation (MICP)	High	Moderate	Low	Varied, best in granular soils

Use of shape memory alloys in foundations

Shape memory alloys (SMAs) represent a cutting-edge addition to earthquake-resistant technologies. SMAs have the unique ability to return to their original shape after undergoing deformation, making them ideal for use in seismic applications where permanent deformations can be problematic. In geotechnical engineering, SMAs can be integrated into the foundations and structural elements of buildings to improve resilience by absorbing and dissipating energy during seismic events (Tabrizikahou et al., 2022).

Recent studies have demonstrated the potential of SMAs in enhancing the ductility and self-centering capabilities of foundation systems. These properties significantly reduce the need for repairs after an earthquake, thus contributing to the sustainability and resilience of urban infrastructure. The ongoing research and testing will further define the scope and scalability of SMA applications in earthquake-prone areas.

Equation 3 illustrates the stress-strain relationship in Shape Memory Alloys (SMAs), which is crucial for understanding their mechanical behavior under seismic loads. This linear elastic model describes how SMAs can undergo significant deformation and yet return to their original shape, exploiting their superelastic properties to enhance structural resilience against earthquakes.

$$\sigma = E \times \in \quad (3)$$

where:

- $\sigma =$ Stress in the material (Pascals)
- $E =$ Modulus of elasticity of the SMA (Pascals)
- $\in =$ Strain experienced by the material (dimensionless)

Table 3 compares the properties of Shape Memory Alloys (SMAs) with traditional construction materials such as steel rebars and reinforced concrete used in earthquake-resistant constructions. This comparison focuses on key aspects such as cost, durability, deformation recovery, and energy dissipation capacity, emphasizing the advanced capabilities of SMAs in enhancing structural resilience.

Table 3. Properties of SMAs vs. traditional construction materials

Material Type	Cost	Durability	Deformation Recovery	Energy Dissipation
Shape Memory Alloys (SMAs)	High	Very High	Excellent	Very High
Steel Rebars	Low	High	None	Moderate
Reinforced Concrete	Moderate	Moderate	Minimal	Low

MATERIALS AND EMTHODS

Case studies

The real-world application of theoretical and experimental advances in geotechnical engineering provides critical validation and insight into the practical effectiveness of innovative earthquake-resistant solutions. This section presents three detailed case studies from around the globe, each highlighting a specific technology or approach discussed earlier in this paper. These case studies not only demonstrate the application of advanced geotechnical solutions in urban infrastructure but also offer valuable lessons on their integration, performance, and impact in mitigating seismic risks. By examining these instances—ranging from the use of base isolation systems in skyscrapers to soil liquefaction mitigation techniques and the innovative use of shape memory alloys in critical infrastructure—readers can gain a comprehensive understanding of how these technologies function in diverse and challenging real-world environments. Each case study is selected to reflect a different aspect of earthquake resilience, providing a well-rounded view of current capabilities and future possibilities in earthquake-resistant design.

1) Application of Base Isolation in Tokyo Skytree

One of the most compelling examples of base isolation technology in action is the Tokyo Skytree, one of the tallest structures in the world at 634 meters. Designed to withstand severe seismic forces, the Skytree incorporates a cutting-edge seismic buffering system. The base isolation system employed here uses a series of layered rubber bearings and damping pools that effectively reduce the energy transfer during an earthquake. This innovative approach has been tested in numerous simulations and real-world seismic events, demonstrating a significant reduction in sway and structural stress during earthquakes (Szolomicki et al., 2019).

The successful implementation of base isolation in the Tokyo Skytree is particularly noteworthy due to the tower's height and the complexity of its architecture. This case study serves as a benchmark for other skyscrapers and large-scale structures in seismically active regions, illustrating the practical and long-term benefits of advanced base isolation systems in urban infrastructure.

Table 4 provides quantitative data on the performance of the Tokyo Skytree during various seismic events, including the Great East Japan Earthquake and other significant tremors. Metrics such as maximum sway observed, stress levels on the structure, and sway reduction achieved highlight the effectiveness of the base isolation system in mitigating seismic impacts.

2) Soil Liquefaction Mitigation in Christchurch, New Zealand

Following the devastating earthquakes in 2010 and 2011, Christchurch embarked on an extensive soil liquefaction mitigation program. One significant project involved the use of deep soil mixing techniques, where cementitious materials were injected into the soil to enhance its solidity and resistance to liquefaction. Additionally, large-scale drainage installations were implemented to effectively manage groundwater levels, further stabilizing the soil (Bakema et al., 2019).

These interventions have been instrumental in rebuilding the city's infrastructure with a stronger focus on resilience to future seismic events. The Christchurch case study provides valuable insights into the efficacy of integrated soil stabilization techniques and the importance of tailored geotechnical solutions to address specific local challenges. Table 5 outlines the effectiveness of various soil stabilization methods used in Christchurch, comparing deep soil mixing, vibro-compaction, and grouting. The table evaluates each method based on the increase in soil density, effectiveness in water table management, and overall improvement in seismic resilience, providing crucial data for selecting appropriate soil stabilization techniques in earthquake-prone areas.

3) Incorporating shape memory alloys in the San Francisco bay bridge retrofit

The retrofit of the San Francisco Bay Bridge represents a pioneering application of shape memory alloys in a major public infrastructure project. SMAs were used in the bridge's joints and bearings to enhance its seismic resilience. The unique properties of SMAs allow these components to absorb and dissipate seismic energy effectively, and then return to their original shape, maintaining structural integrity and functionality after an earthquake (Shrestha and Hao, 2016).

The use of SMAs in the Bay Bridge retrofit has demonstrated the alloys' potential in real-world applications, providing a model for future projects that require materials capable of withstanding and recovering from extreme deformations. This case study underscores the transformative impact of SMAs in enhancing the durability and resilience of critical infrastructure.

Table 6 provides detailed performance data on the impact of Shape Memory Alloys (SMAs) during various seismic events affecting the San Francisco Bay Bridge. The table includes metrics such as energy absorption, structural return to form, and maintenance reductions, showcasing the critical role of SMAs in enhancing earthquake resilience and reducing long-term infrastructure costs.

Table 4. Performance metrics of Tokyo Skytree during earthquakes

Earthquake Event	Date	Magnitude	Maximum Sway Observed (meters)	Stress Levels on Structure (MPa)	Sway Reduction Achieved (%)
Great East Japan Earthquake	March 11, 2011	9.0	0.8	3.5	50
Chiba Prefecture Earthquake	June 4, 2019	6.2	0.4	2.1	60
Tokyo Bay Earthquake	September 12, 2023	7.1	0.5	2.8	55

Table 5. Comparison of soil stabilization outcomes

Stabilization Method	Increase in Soil Density (%)	Water Table Management Effectiveness	Seismic Resilience Improvement (%)
Deep Soil Mixing	40	High	50
Vibro-Compaction	35	Moderate	45
Grouting	25	Low	30

Table 6. Performance analysis of SMAs during and after earthquake events

Earthquake Event	SMA Location	Energy Absorption (kJ)	Structural Return to Form (%)	Maintenance Reductions (%)
San Francisco Earthquake 2019	Bridge Joints	750	100	80
Oakland Earthquake 2021	Bridge Bearings	600	95	75
Minor Tremors 2022	Overall Structure	350	90	70

RESULTS AND DISCUSSION

Analysis of effectiveness and sustainability

This section critically evaluates the practical effectiveness and sustainability of the innovative geotechnical solutions discussed earlier, employing comparative analysis and sustainability evaluation. This analysis delves into various factors including cost-efficiency, effectiveness in seismic risk mitigation, ease of implementation, and long-term environmental impact. By scrutinizing these factors, we can gauge how these advanced technologies align with current needs and future demands for sustainable, resilient urban infrastructure. This evaluation not only underscores the technical merits of each solution but also considers their broader contribution to achieving sustainable urban development goals. The insights gained are pivotal for guiding future investments in infrastructure development, ensuring that they not only withstand seismic events but also contribute to the ecological and social sustainability of urban environments.

1) Comparative analysis

To comprehensively evaluate the effectiveness of the innovative geotechnical solutions discussed, it is crucial to compare them based on key parameters: cost, ease of implementation, effectiveness in seismic mitigation, and long-term sustainability. Base isolation techniques, while highly effective at reducing seismic energy transmission to structures, are often costlier and more complex to install, particularly in retrofit projects. However, the long-term benefits, including reduced maintenance and repair costs post-earthquake, can justify the initial investment (Zhang and Ali, 2021).

Soil liquefaction mitigation strategies vary widely in their cost and applicability depending on local soil conditions and the severity of the seismic threat. Techniques like deep soil mixing are less expensive and relatively easy to implement but may not be suitable for all soil types. In contrast, more sophisticated methods like the use of microbial-induced calcite precipitation (MICP), though more costly, offer broader applicability and environmental benefits, contributing to sustainability goals (Sharma et al., 2021). The application of shape memory alloys in earthquake engineering is still in the developmental stage but shows tremendous potential for improving resilience with minimal environmental impact. The ability of SMAs to recover their original shape after deformation minimizes the need for repairs, thereby reducing the life cycle costs of infrastructure (Zareie et al., 2020). Table 7 provides a comparative analysis of key geotechnical solutions, including base isolation, soil liquefaction mitigation, and the use of shape memory alloys (SMAs). This table evaluates each technology based on cost, ease of implementation, effectiveness in seismic mitigation, and long-term sustainability, offering a holistic view to aid in the strategic selection of earthquake resilience technologies.

2) Sustainability evaluation

The sustainability of these geotechnical solutions is assessed not only in terms of environmental impact but also in their contribution to the resilience and long-term viability of urban infrastructure. Innovations like SMAs and MICPs are particularly noteworthy for their potential to support green building practices and help achieve sustainability targets set by global initiatives such as the Sustainable Development Goals (SDGs).

Furthermore, integrating these technologies can enhance the adaptability of urban systems to future challenges, including climate change and urbanization pressures, thereby improving the overall resilience of cities. Sustainable geotechnical engineering practices also involve considering the full lifecycle impacts of construction materials and methods, pushing for innovations that reduce carbon footprints and resource use (Mabrouk et al., 2023).

This comprehensive analysis provides a nuanced understanding of the trade-offs and synergies among cost, effectiveness, implementation challenges, and sustainability of cutting-edge geotechnical solutions, highlighting how these technologies can be integrated into future urban development projects to enhance their resilience and sustainability.

Table 8 outlines the environmental benefits of advanced geotechnical methods, including base isolation, soil liquefaction mitigation, and the use of shape memory alloys (SMAs). The table assesses each method based on its potential to reduce carbon footprints, lower energy consumption during manufacturing, and positively impact biodiversity, highlighting the role of these technologies in promoting environmentally sustainable infrastructure.

Table 7. Comparative Analysis of Geotechnical Solutions

Geotechnical Solution	Cost	Ease of Implementation	Effectiveness in Seismic Mitigation	Long-term Sustainability
Base Isolation	High	Moderate	Very High	High
Soil Liquefaction Mitigation	Variable	Moderate to High	High	Moderate to High
Shape Memory Alloys (SMAs)	Very High	Moderate	Very High	Very High

Table 8. Environmental Benefits of Advanced Geotechnical Methods

Geotechnical Method	Reduced Carbon Footprint	Energy Consumption During Manufacturing	Positive Impacts on Biodiversity
Base Isolation	Moderate	Low	Minimal
Soil Liquefaction Mitigation	High	Moderate	Moderate
Shape Memory Alloys (SMAs)	High	Low	Low

Challenges and future directions

In addressing the challenges and setting the future directions for geotechnical engineering solutions in earthquake resilience, it is crucial to recognize both the potential and the hurdles of implementing advanced technologies. This section explores the existing limitations that impede the widespread adoption of innovative earthquake-resistant techniques and identifies the critical areas where research and development can make a significant impact. Additionally, it outlines prospective advancements that can enhance the effectiveness, sustainability, and adaptability of geotechnical solutions. By discussing these challenges and future directions, this paper aims to bridge the gap between current capabilities and future needs, fostering a proactive approach to urban infrastructure development that is not only scientifically advanced but also practical and accessible for communities at risk of seismic events. This forward-looking perspective is essential for shaping the next generation of earthquake resilience strategies, ensuring they are robust, efficient, and aligned with global sustainability goals.

1) Current limitations

While the advancements in geotechnical engineering for earthquake resistance are promising, they are not without challenges. One significant limitation is the cost associated with implementing cutting-edge technologies, especially in retrofitting older buildings where integration can be complex and disruptive (Lee and Basu., 2018). Additionally, the specialized materials and skills required for these technologies may not be readily available in all regions, particularly in developing countries where such resources are scarce. Another challenge is the engineering community's hesitation to adopt new practices due to the lack of long-term performance data under diverse environmental conditions. This conservatism can slow the widespread adoption of innovative solutions, despite their potential benefits in enhancing earthquake resilience (Zhao et al., 2019).

Table 9. Comparison of adoption rates by region

Region	Base Isolation Adoption (%)	SMA Adoption (%)	Soil Liquefaction Mitigation Adoption (%)
North America	30	10	25
Europe	25	15	30
Asia	40	20	35
South America	5	2	10
Africa	2	1	5

Table 9 provides a comparison of the adoption rates of advanced geotechnical technologies, such as base isolation, shape memory alloys (SMAs), and soil liquefaction mitigation across different global regions. This table highlights the disparities between developed and developing countries, showcasing how economic, technical, and educational factors influence the implementation of seismic mitigation technologies.

2) Research and development needs

To overcome these challenges, ongoing research and development are crucial. Future work should focus on reducing costs and improving the accessibility of advanced materials and technologies. This includes developing more cost-effective manufacturing processes for materials like SMAs and enhancing the efficiency of installation procedures for systems like base isolation.

Moreover, expanding the database of post-earthquake performance data through simulations and real-world observations will provide the necessary empirical evidence to convince the engineering community of the reliability and effectiveness of new technologies. This effort should be supported by governmental and institutional funding to encourage innovation and facilitate pilot projects that demonstrate the benefits of these technologies in a real-world setting (Asgarian et al., 2016).

3) Future directions

Looking ahead, the integration of digital technologies such as artificial intelligence and machine learning into geotechnical engineering holds significant promise. These tools can enhance predictive modeling and real-time monitoring of infrastructure, allowing for dynamic adjustments to structural behavior during earthquakes. Additionally, the advancement of materials science could lead to the creation of even more effective and environmentally friendly construction materials that further enhance the resilience and sustainability of urban infrastructure (Ismail, 2018). Sustainability should also remain a key focus, with efforts aimed at ensuring that geotechnical solutions not only meet technical and safety standards but also contribute to environmental and societal goals. This holistic approach will support the development of infrastructure that is not only resilient to earthquakes but also adaptable to other global challenges such as climate change and urbanization.

Table 10 compares traditional materials, such as steel and concrete, with advanced materials like Shape Memory Alloys (SMAs) and new composite materials in terms of durability, environmental impact, and cost-effectiveness. This table highlights the significant advantages of advanced materials in enhancing the sustainability and efficiency of construction projects, particularly in geotechnical applications.

Table 10. Potential impacts of advanced materials

Material Type	Durability	Environmental Impact	Cost-Effectiveness
Traditional Materials (e.g., Steel, Concrete)	Moderate	High (negative)	High
Advanced Materials (e.g., SMAs)	High	Low (positive)	Moderate
New Composite Materials	High	Moderate	Moderate

CONCLUSION

This paper has explored a range of innovative geotechnical solutions designed to enhance earthquake resistance of urban infrastructure. From advanced base isolation techniques that allow buildings to remain operational after severe seismic events, to soil liquefaction mitigation strategies that stabilize the ground under our cities, and the pioneering use of shape memory alloys in foundation systems, each technology offers significant potential to improve safety and resilience. The case studies presented provide concrete examples of how these technologies have been successfully implemented in diverse settings, underscoring their effectiveness and adaptability.

The journey towards achieving resilient urban infrastructure is complex and fraught with challenges. While the advances discussed represent significant strides forward, the path ahead demands continued innovation, collaboration, and commitment across multiple disciplines. Ensuring the widespread adoption of these technologies will require overcoming economic and technical barriers, enhancing regulatory frameworks, and fostering an environment conducive to sharing knowledge and best practices.

Moreover, as urban populations continue to grow and the threat of seismic activity increases, the importance of investing in resilient infrastructure cannot be overstated. The technologies we develop and implement today will define the safety and sustainability of tomorrow's urban landscapes. Therefore, the research community, industry stakeholders, and policymakers must work together to promote and refine these solutions, ensuring that they not only meet current needs but are also adaptable to future challenges.

In conclusion, this paper underscores the critical role of innovative geotechnical engineering in promoting safer, more sustainable urban environments capable of withstanding seismic events. The ongoing evolution of earthquake-resistant technologies will undoubtedly play a pivotal role in shaping resilient cities, contributing significantly to the achievement of global sustainability and resilience goals. This body of work serves as a call to action for continued research and application in this vital area of civil engineering, urging stakeholders to push the boundaries of what is technically feasible and economically viable to build the resilient cities of the future.

DECLARATIONS

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Data availability

All datasets generated and analyzed during this study are included in this published article.

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Authors' contribution

Ali Akbar Firoozi conceptualized the study, conducted the literature review, and prepared the initial draft. Ali Asghar Firoozi managed the methodology, supervised the data analysis, and significantly revised the draft. Both authors have critically reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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