ISSN 1840-4855
e-ISSN 2233-0046

Original scientific article
http://dx.doi.org/10.70102/afts.2025.1834.939

GEOTECHNICAL APPROACHES FOR BUILDING EARTHQUAKE-RESILIENT INFRASTRUCTURE IN URBAN ENVIRONMENTS

Dr. Jainish Roy[1*], Dr. Rajesh Sehgal[2]

[1]Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.*
e-mail: ku.jainishroy@kalingauniversity.ac.in,
orcid: https://orcid.org/0009-0003-7116-9137
[2]Assistant Professor, Kalinga University, Naya Raipur, Chhattisgarh, India.
e-mail: ku.rajeshsehgal@kalingauniversity.ac.in,
orcid: https://orcid.org/0009-0002-0344-403X

Received: September 27, 2025; Revised: November 01, 2025; Accepted: December 05, 2025; Published: December 30, 2025

SUMMARY

The seismic nature of the soil in urban spheres is very susceptible to seismic ground failures caused by intricate soil conditions, extensive development, and outdated construction methods. However, structural solutions have always played the most important role in seismic design; growing evidence points to the importance of geotechnical engineering in the development of earthquake-resilient urban infrastructure. In this paper, a synthesis of geotechnical methods of earthquake resilience is given based on the seismic hazard evaluation, mitigation of liquefaction, ground improvement, foundation, and soil structure interaction. The analyzed literature shows that seismic demand in urban regions may differ by 24 times depending on the specific conditions of the soils in various micro zones. Sites that contain Vs30 less than 180 m/s are always highly amplified on the ground and prone to liquefaction. The techniques of liquefaction mitigation are proven to be very effective. Densification methods reduce the settlement by 30-50 %, drainage systems achieve 40-70 % reduction of excess pore water pressure, and soil stabilization methods yield up to 60-80 % settlement reduction. Ground improvement techniques increase the soil stiffness in the range of 1.5-3.0 times, whereas pile-raft foundation systems minimize seismic settlement, 20-40 % as compared to a shallow foundation. The fact that soil structure interaction is considered changes the structural natural periods by 10-30% by an important factor in seismic response. The results point out that the site-specific geotechnical interventions will be necessary to minimize the seismic damage and enhance the post-earthquake performance. The research offers a technical foundation of how to incorporate geotechnical solutions in the urban seismic resilience planning and aids the wise choice of safer and more sustainable cities.

Key words: *geotechnical earthquake engineering, urban seismic resilience, soil liquefaction, ground improvement, seismic microzonation, soil–structure interaction.*

INTRODUCTION

City settlements in seismic zones are now more susceptible to the destruction of earthquakes because of the high population density, the ground situation, and aging infrastructure. This has been demonstrated by experience with recent earthquakes, which frequently control the extent of damage by the behavior of local soils and foundation performance, and not just by the magnitude of the earthquake. Consequently, earthquake-resistant infrastructure development is now less structural in nature, but rather incorporates integrated methods that have integrated the importance of geotechnical engineering to help prevent ground-related failures [1][17]. Traditional seismic design is primarily focused on the response of the superstructure, whereas failures associated with liquefaction of soils, excessive settlement, lateral spreading, and soil-structure interaction still led to severe losses, especially in urban settings where soils are not homogeneous, and the groundwater table is not deep [18]. Even though seismic isolation, energy dissipation, and advanced structural materials can decrease seismic demand, their performance is highly determined by the behavior of the ground and basing [2]. On the same note, seismic safety is also taken into account in the architectural and energy-saving building designs, yet its functionality depends on the proper geotechnical support [5]. The latest research brings up the importance of combined resilience models, which would integrate geotechnical engineering, structural design, urban planning, and sustainability-related issues [4][9]. The developments in GIS-based hazard mapping, geospatial soil modeling, and data-driven analysis techniques have enhanced the process of detecting high-risk urban areas and have helped to plan mitigation efforts more intelligently [8]. Simultaneously, economic and educational approaches underline that resilient infrastructure must be sustainable, safe, and able to benefit society both in the short and long term [14][19], and the emerging study of subsurface systems and post-earthquake soil behavior also enlarges the focus of geotechnical earthquake engineering [3][13]. Although much has been researched, there is little consensus and synthesis of technologies that look at the geotechnical solutions to earthquake-resistant urban infrastructure. The paper fills this gap by (i) synthesizing the current advances in seismic hazard assessment, liquefaction mitigation, ground improvement, foundation systems, and soil-structure interaction; (ii) reviewing their effectiveness and applicability in urban settings, and (iii) identifying the new trends in data-driven analysis and sustainability-oriented geotechnical practices. The structure of the paper is the following: Section 2 contains the review of related literature; Section 3 is concerned with the seismic hazard assessment and site characterization methods; Section 4 deals with the key geotechnical approaches; Section 5 summarizes major findings and results; and Discussion, Conclusion, and Future Research of the paper can be found in Sections 6.

LITERATURE REVIEW

The structural, architectural, and urban perspective of earthquake-resilient infrastructure has been largely researched in literature, but recent literature shows an increasing prominence of geotechnical engineering as a key factor that regulates seismic behaviour. Firoozi [1] underlines that ground-related failures, including liquefaction, settlement, and subsequent lateral spreading, tend to be dominant in quake effects in urban-based earthquakes, and thus, geotechnical innovation is required in seismic design. Resilience measures that are structural in nature, such as seismic isolation and energy dissipation systems, have also been thoroughly examined and demonstrated to have a strong reduction of structural demand [2][10]. Strength and sustainability of earthquake-resistant systems have also been enhanced due to optimization of high-performance structural components [6]. Seismic considerations are also integrated in the architectural guidelines and the concept of near-zero energy buildings, which recognizes the increased application of safety and sustainability in the design of buildings [12]. Nevertheless, such methods usually presuppose steady-state ground conditions and are limited in the treatment of soil behavior under strong seismic loading. The topics that have been covered in geotechnical studies of earthquake engineering encompass seismic behaviour of soils, underground structures, and foundation systems.

Zheng et al. [3] emphasize the significance of robust assessment and management approaches to geotechnical and underground systems, whereas Jamil [11] records the real-life difficulties of developing areas where the failures of the ground enhance the seismic hazard. Other recent studies also look at the long-term transformations of the soil properties after the occurrence of earthquakes, which suggest consequences on the stability of the post-event and environmental soundness [13]. The GIS-based and geospatial modeling methods have helped advance seismic hazard assessment. Recent studies combine soil plasticity information with water content and urban land-use data to aid resilient infrastructure planning [16][18], although demonstrating the usefulness of the GIS-based geotechnical hazard screening at an earlier stage, Wilding and Luna [20] did. Machine learning methods based on data and integrating in-situ testing with machine learning have also enhanced the prediction of liquefaction risk and fast urban-scale assessment [15]. In addition to engineering actions, larger resilience models also include maintenance planning, asset management, and rapid assessment of damages to increase the response and recovery after an earthquake [4][8]. Economic analyses prove that the benefit-cost analysis of the earthquake-resilient design and retrofitting gives positive results throughout the infrastructure lifecycle [14]. The perspectives of education and professional practice also emphasize the necessity of resilience-driven engineering solutions based on the experience of the recent major earthquakes [7][9]. As can be seen in the reviewed literature, even though immense efforts have been made in the structural and resilience-based earthquake engineering, geotechnical factors are generally regarded as secondary or disjointed factors. It is evident that there is a necessity for a synthesis approach that considers geotechnical methods as the key features between hazard assessment and ground enhancement, and soil-structure interaction as key components of the execution of earthquake-resistant urban infrastructure. This is the gap that has given the impetus to the current study.

SEISMIC HAZARD ASSESSMENT AND SITE CHARACTERIZATION

The technical background of designing urban infrastructure resilient to earthquakes comprises seismic hazard assessment and site characterization. Underground conditions in urban settings tend to be of high spatial variability because of the natural processes of deposition and human-origin alterations. It, therefore, follows that a regional seismic hazard map is not enough, and site-specific geotechnical analysis is required to have a good predictability of amplification of the ground movements, failure processes of soils, and foundation responsiveness during earthquakes. This segment introduces the most significant elements of seismic hazard evaluation that are applicable to urban geotechnical engineering, such as seismic microzonation, GIS-based soil mapping, and data-driven soil risk assessment. Where required, standard mathematical formulations are presented that ensure engineering interpretation and do not attempt to be too analytical in their complexity.

Seismic Microzonation in Urban Areas

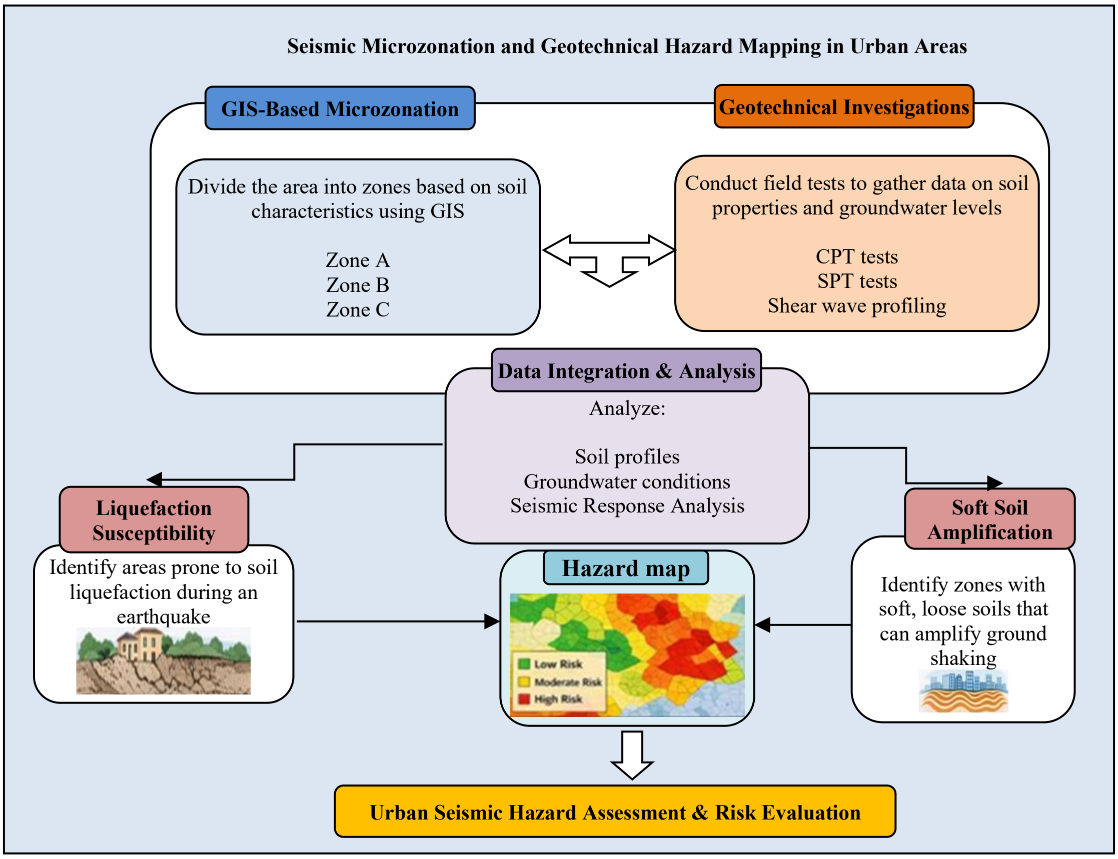

Figure 1. Seismic microzonation and geotechnical hazard mapping framework for urban environments

Seismic microzonation is the division of an urban area into similar seismic response zones as per geological, geotechnical, and geophysical conditions. As opposed to uniform design spectra, microzonation is able to capture local site effects that can play a significant role in the damage distributions of earthquakes, especially in cities with soft soils, reclaimed land, or shallow groundwater conditions present. The main parameters that are taken into consideration in urban seismic microzonation are: Stratigraphy and thickness of the soft deposits in soil. Profiles of shear velocity wave (Vs and Vs30). Depth to bedrock, groundwater table depth, past seismicity, and distribution of damage. The results of microzonation are usually in the form of low, moderate, and high seismic hazard zones, which are used on a technical basis in planning land-use and selection of foundation and a focused mitigation strategy.

Figure 1 demonstrates the Seismic microzonation and geotechnical hazard mapping system of the urban environment, which reveals the combination of geotechnical studies, GIS-based zoning, and seismic hazard scale.

GIS-Based and Geospatial Soil Mapping

Geographic Information Systems (GIS) can be used to integrate and visualize geotechnical data that is distributed spatially to carry out the assessment of seismic hazards. Urban areas' GIS-based soil mapping aids in interpolating subsurface properties, as well as locating areas where the soil is likely to liquefy, experience excessive settlement, or amplify the ground motion.

Typical GIS layers used in geotechnical seismic assessment include:

- Borehole and in-situ test data (SPT, CPT)
- Shear wave velocity measurements
- Groundwater depth distribution
- Surface geology and land-use patterns

GIS is more effective in decision-making, as it provides the possibility to perform multi-criteria analysis, as well as to correlate the conditions of the soil and the most important urban infrastructure directly.

Data-Driven Soil Risk Evaluation and Liquefaction Assessment

The central elements of seismic site characterization of urban settings include liquefaction risk assessment, mostly in saturated sandy and silty soils. The liquefaction triggering potential is usually measured using standard analytical formulations depending on seismic loading and resistance of the soil.

The cyclic stress ratio (CSR), representing earthquake-induced cyclic demand, is calculated as in Eqn 1:

$$CSR = 0.65 \cdot \frac{a_{max}}{g} \cdot \frac{\sigma_v}{\sigma_v'} \cdot r_d \qquad (1)$$

where:

a_{max}= peak horizontal ground acceleration,

g= acceleration due to gravity,

σ_v= total vertical stress,

σ_v'= effective vertical stress,

r_d= stress reduction factor.

The factor of safety against liquefaction (FS_L) is then expressed as in Eqn 2:

$$FS_L = \frac{CRR}{CSR} \qquad (2)$$

where $CRR$is the cyclic resistance ratio obtained from in-situ test correlations. Recent developments have involved data-based and machine learning methods to enhance the accuracy of prediction through the nonlinear association between soil parameters and attempted seismic performance. Such methods improve the traditional methods by minimizing uncertainty and assisting in the rapid screening of risks at urban levels. Table 1 enumerates Geotechnical parameters applied in the characterization of the seismic sites that normally include soil and seismic parameters with their ranges and engineering implications. The urban geotechnical studies are synthesized into SPT, CPT, and Vs30 ranges [1][18]. Parameters of liquefaction (CSR and FS -) are formed on the basis of popular values that are reported in recent liquefaction evaluation literature [15][20].

Table 1. Geotechnical parameters used in seismic site characterization

Parameter	Typical Urban Range	Test / Source	Engineering Significance
SPT-N value	5–30 blows	Standard Penetration Test	Soil density and liquefaction resistance
CPT tip resistance (qc)	2–25 MPa	Cone Penetration Test	Soil strength and stratification
Shear wave velocity (Vs30)	150–450 m/s	MASW / Downhole tests	Site classification and amplification
Groundwater depth	1–10 m	Observation wells	Liquefaction susceptibility
Plasticity Index (PI)	5–35 %	Laboratory tests	Cyclic soil behavior
Cyclic Stress Ratio (CSR)	0.10–0.40	Seismic analysis	Earthquake-induced demand
Factor of Safety (FS_l)	<1.0–>1.5	Analytical evaluation	Liquefaction triggering risk

Engineering Implications for Urban Seismic Design

Geotechnical and structural design is made in urban settings directly based on the results of seismic hazard evaluation and site characterization. The areas with seismic amplification or liquefaction potential are considered zones of special needs that need specific mitigation measures, which can be ground improvement, deep foundations, or altered seismic design spectra. On the other hand, in low-hazard zones, the best and cost-efficient foundation solutions can be optimized. Using seismic microzonation, GIS-based soil mapping, and performance-driven risk analysis, engineers can use a performance-based approach to geotechnical design that can increase the urban seismic performance and stability, as well as balance safety, constructability, and sustainability.

GEOTECHNICAL APPROACHES FOR EARTHQUAKE-RESILIENT INFRASTRUCTURE

Geotechnical strategies represent the key engineering strategies for reducing ground failures caused by earthquakes and improving the seismic resilience of urban infrastructure. Geotechnical interventions are used to directly mitigate the effects of subsurface hazards like soil liquefaction, excessive settlement, lateral spreading, and soil foundation instability, unlike structural systems, which primarily manage geotechnical superstructure response. In the crowded urban areas, these solutions need to be both technically functional and space-efficient, and in relation to the existing infrastructure.

Figure 2 Geotechnical methods of earthquake-resistant infrastructure, an example of soil liquefaction prevention, ground improvement methods, earthquake-resistant foundation systems, and effects on soil and structure interactions.

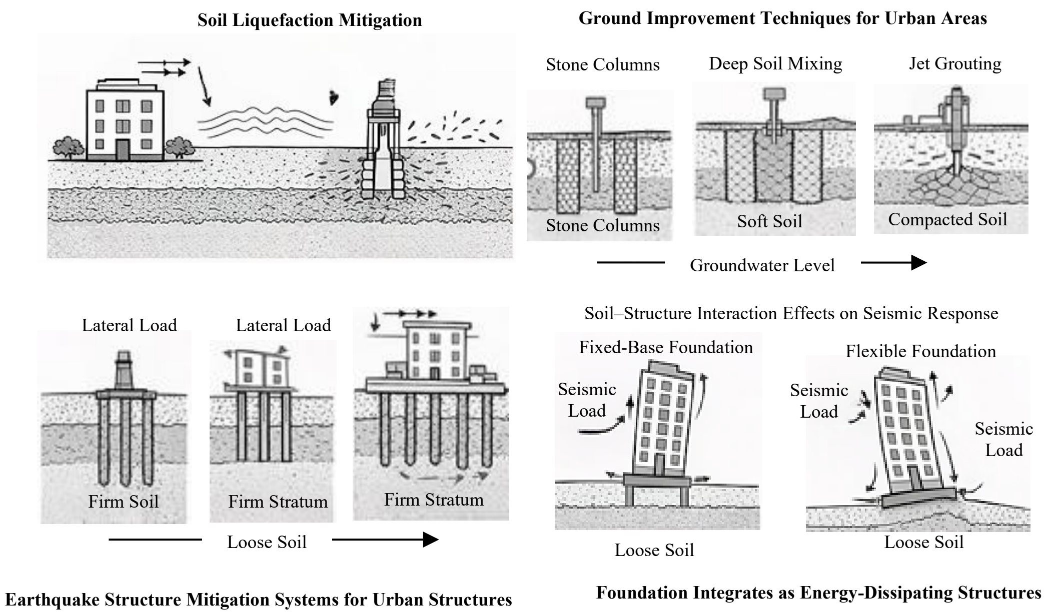

Figure 2. Geotechnical approaches for earthquake-resilient infrastructure

Soil Liquefaction Mitigation Techniques

The most severe type of geotechnical failure mechanism during earthquakes is soil liquefaction, which occurs especially when the soil is saturated and is made up of loose sands and silty soils, which is typical of urban alluvial and coastal areas. Liquefaction causes an abrupt loss of soil strength and stiffness, causing settlement of the foundations, tilting, lateral spreading, and destruction of the underground utility. The choice of the liquefaction mitigation techniques is determined by the factor of safety against liquefaction (FS_L) derived from seismic site characterization (Section 3). Some of the typical methods are densification, an increase in drainage, and soil stabilization. Generally, mitigation methods that have low vibration and disturbance to the ground are favored in the urban setting.

Ground Improvement Techniques for Urban Environments

Increased seismic loading of soil. Ground improvement techniques improve soil stiffness, strength, and resistance to deformation. These are effective methods for the urban setting where deep foundations might be limited due to cost, access, or other construction constraints. An equation of state can be simplified and adopted as in the expression of the improvement in soil stiffness in terms of a simplified equation in form of an equation of state in the form of Eqn 3:

$$G_{improved} = \alpha\, G_{natural} \quad (3)$$

Where:

$G_{Improved}$ is the shear modulus of the improved soil,

$G_{natural}$is the shear modulus of untreated soil, and

$\alpha$is the improvement factor, typically ranging from 1.5 to 3.0 depending on the technique used.

Some of the most widely used techniques are the stone columns, deep soil mixing, and jet grouting, as each technique has varying degrees of enhancement and constructability in tight urban areas.

Earthquake-Resistant Foundation Systems

During earthquakes, foundation systems are the important interface between the buildings and the ground that supports them. The foundation design that is resistant to earthquakes is designed to safely transfer seismic forces and, at the same time, ensure that the deformation of the ground is accommodated without damaging the foundation too much. When the soil is in seismic conditions, the bearings that can be used are usually lowered by the seismic reduction factor in the form of Eqn 4:

$$q_{allow,seismic} = \frac{q_{static}}{F_s} \cdot \eta_s \qquad (4)$$

Where:

$q_{allow,seismic}$ is the allowable bearing capacity under seismic loading,

q_{static} is the static allowable bearing capacity,

F_s is the factor of safety, and

η_s is the seismic reduction factor (typically 0.7–0.9).

Soil–Structure Interaction Effects

The seismic performance of urban infrastructure is greatly affected by soil-structure interaction (SSI) in relation to soft soils or stratified soils. SSI changes structural natural periods, damping features, and seismic demand. The change in structural natural period caused by SSI may be indicated as being in the form of Eqn 5:

$$T_{SSI} = T_f \sqrt{1 + \frac{k_s}{k_f}} \qquad (5)$$

Where:

T_{SSI} is the natural period considering SSI,

T_f is the fixed-base natural period,

k_s is the soil stiffness, and

k_f is the foundation stiffness. Taking into account that SSI results in more realistic seismic performance predictions, the underestimation of displacement demand is unsafe. Table 2 shows the suitability of geotechnical methods to earthquake-resistant urban infrastructure that compares geotechnical methods on the basis of their purposes, suitability of soils, applicability in the city, and seismic advantages.

Engineering Significance of Geotechnical Approaches

Likewise, the efficiency of the geotechnical strategies is based on the combination with the seismic hazard evaluation and structural design. When these methods are picked up, depending on the site-specific soil properties and seismic demand, the methods will substantially minimize the earthquake-related damage and improve the operation of posts after an earthquake. Geotechnical interventions deliver an effective solution to earthquake-resistant infrastructure in urban conditions that is cost-efficient and viable.

Table 2. Applicability of geotechnical approaches for earthquake-resilient urban infrastructure

Geotechnical Approach	Primary Objective	Suitable Soil Conditions	Urban Applicability	Seismic Benefit
Densification (vibro / dynamic)	Increase soil density	Loose sands	Moderate	Reduced liquefaction settlement
Drainage systems	Dissipate pore pressure	Saturated sands	High	Liquefaction control
Stone columns	Improve strength and drainage	Soft clays, silts	High	Increased shear resistance
Deep soil mixing	Strength and stiffness enhancement	Soft clays	Moderate	Settlement reduction
Jet grouting	Localized strengthening	Variable soils	High	High deformation control
Pile foundations	Load transfer to competent strata	Weak surface soils	High	Foundation stability
Pile–raft systems	Load sharing and settlement control	Mixed soil profiles	High	Enhanced seismic performance

RESULTS AND KEY FINDINGS

This part also contains the most important findings obtained through comparative synthesis of recent geotechnical earthquake engineering, as opposed to recent experimental or numerical research. The findings report performance differences, effectiveness margins, and multi-criteria engineering trade-offs relating to the seismic hazard evaluation and geotechnical mitigation measures in an urban setup. The results are aimed at informing engineering decision-making and bringing out prevailing trends in the literature. All the illustrative graphs in this section were created using Python with the Matplotlib library to illustrate the synthesized performance ranges in the literature.

Results of Seismic Hazard Assessment and Site Characterization

The synthesis of seismic microzonation and site characterization results in urban areas demonstrates a high level of spatial variability of seismic demand in metropolitan areas. The amplification of ground motion and the susceptibility to liquefaction are heavily dependent on the nature of local soil conditions, the shear wave velocity, and the depth of groundwater.

Key findings

The seismic demand is differentiated by some 2-4 times in the various micro zones of a city.

Sites with Vs30 that are less than 180 m/s are always highly amplified and in danger of liquefaction.

GIS incorporation of geotechnical data is very effective in identifying high-risk areas over homogeneous design spectra. The level of indicative seismic hazards given in Table 3 under seismic hazard characteristics at urban microzonation highlights the typical level of hazards of various seismic microzonation classes.

Table 3. Indicative seismic hazard characteristics across urban microzonation zones

Parameter	Low Hazard Zone	Moderate Hazard Zone	High Hazard Zone
Vs30 (m/s)	>360	180–360	<180
Ground amplification	Low	Moderate	High
Liquefaction susceptibility	Low	Moderate	High
Foundation demand	Low	Moderate	High

Variability in Performance of Liquefaction Mitigation Techniques

Comparative evaluation of the liquefaction mitigation methods shows that although each of the mitigation methods minimizes the seismic-induced deformation, its effectiveness varies with the type of soil, the presence of groundwater, and construction limitations. Notably, there is significant variation in reported performance outcomes in various research.

Key findings

Densification methods normally result in a 30-50 % decrease in the settlement in the aftermath of an earthquake.

Systems of drainage exhibit 40-70 % less excess pore water pressure and settlement.

As a rule, soil mix methods and, to a lesser extent, deep soil mixing, offer the best and most predictable results.

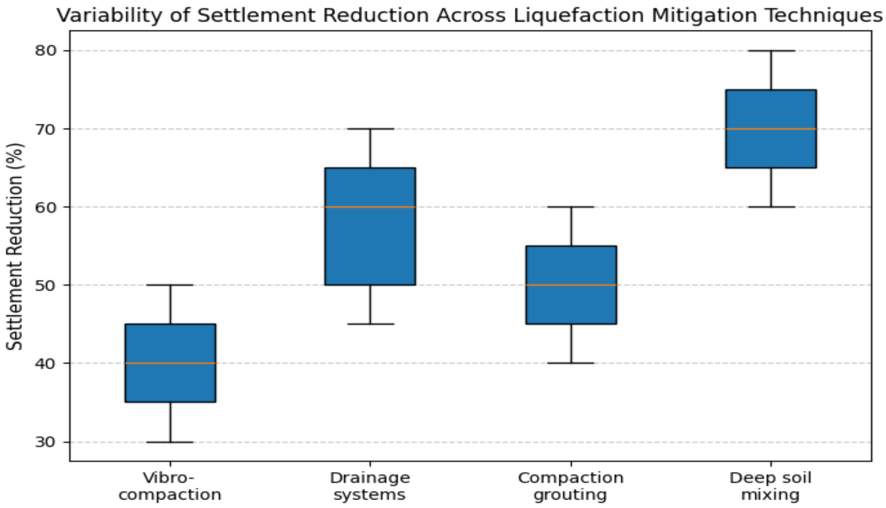

Figure 3. Variability of settlement reduction across liquefaction mitigation techniques, illustrating the range, median, and dispersion of performance reported in recent studies

Figure 3 demonstrates the consistency of the reduction in settlement between the liquefaction mitigation methodologies, their range, and scatter of settlement reduction documented by various liquefaction mitigation techniques, depending on the synthesized literature results. Table 4 presents settlement reduction ranges and ranges of applicability of different liquefaction mitigation methods societally reported.

Table 4. Performance ranges of liquefaction mitigation techniques

Technique	Settlement Reduction Range (%)	Performance Consistency	Urban Suitability
Vibro-compaction	30–50	Moderate	Moderate
Drainage systems	40–70	High	High
Compaction grouting	35–60	Moderate	High
Deep soil mixing	60–80	Very High	Moderate

Multi-Criteria Performance of Ground Improvement Techniques

Ground improvement methods have a clear trade-off when compared in terms of several performance criteria. Some of these approaches offer high mechanical performance, whereas others have benefits in constructability, cost-effectiveness, and suitability in high-density urban settings.

Key findings

Jet grouting is the most desirable method when maximum stiffness and control of deformation are required, and it is more expensive and complicated to build.

Stone columns are balanced in terms of performance, constructability, and urban use.

Deep soil mixing is good for settlement control, but it might be limited due to the cost and space considerations.

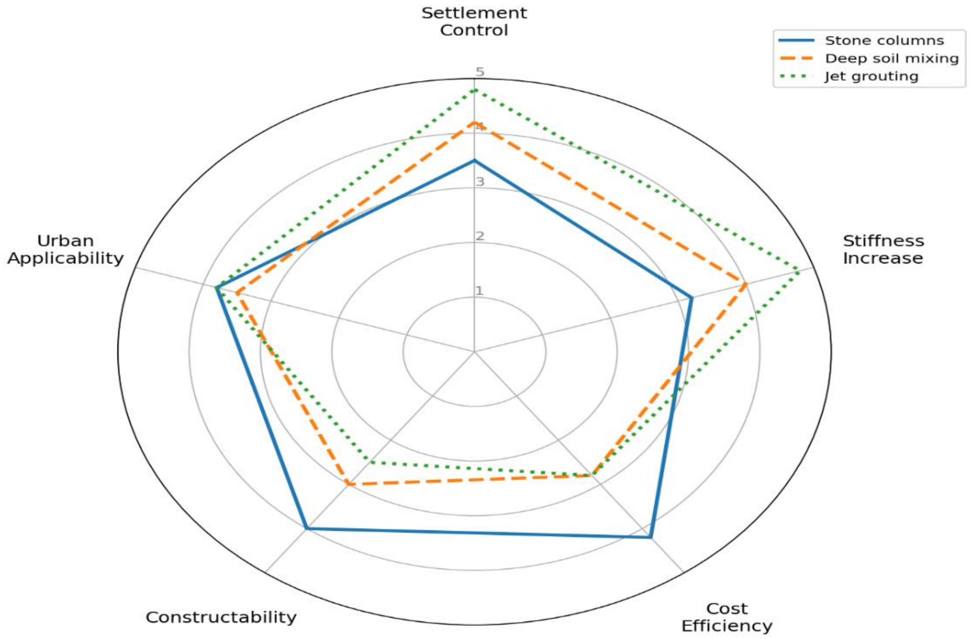

Figure 4. Multi-criteria seismic performance comparison of ground improvement techniques

Figure 4 represents the multi-criteria seismic performance of ground improvement techniques. The radar chart is a comparison of the stiffness increase, settlement control, urban applicability, constructability, and cost efficiency of more popular ground improvement methods. Table 5 is a comparison of various ground improvement techniques based on various performance and constructability measures.

Table 5. Multi-criteria evaluation of ground improvement techniques

Technique	Stiffness Increase	Settlement Control	Urban Applicability	Constructability	Cost Efficiency
Stone columns	Moderate	Moderate	High	High	High
Deep soil mixing	High	High	Moderate	Moderate	Low
Jet grouting	Very High	Very High	High	Low	Low
Controlled modulus columns	High	High	Moderate	Moderate	Moderate

Foundation Systems and Soil–Structure Interaction Outcomes

When soil-structure interaction (SSI) is incorporated into the seismic analysis, there is a pronounced shift in the predicted structural response, especially when using foundations on soft or layered soils such as those of an urban basin.

Key findings

Pile-raft foundation systems minimise seismic settlement up to 20-40% to shallow raft foundations.

The effects of SSI change structural natural periods by 10-30 %, which affects the demand for displacement and the distribution of forces.

Failure to take care of SSI can lead to non-conservative urban site design of soft soil.

Table 6. Seismic performance of foundation systems

Foundation System	Settlement Control	SSI Sensitivity	Urban Applicability
Shallow raft	Low	High	Moderate
Pile foundation	High	Medium	High
Pile–raft system	Very High	Low	High

Table 6 compares the types of foundation on the basis of settlement control, sensitivity to soil structure interaction, and the suitability for urban applications. The results of the synthesis have shown that geotechnical interventions are significant and contribute to the strengthening of earthquake-prone infrastructural systems in the city in the case of site-specific hazard evaluation. The effectiveness of liquefaction mitigation varies according to the technique; the ground improvement technique has obvious multi-criteria trade-offs, and SSI-conscious foundation design can greatly enhance the seismic performance. The results offer a sound technical foundation for the method of proper geotechnical strategies in high-density urban settings.

CONCLUSION

The paper has offered an in-depth literature review of geotechnical strategies to enhance the resiliency of urban infrastructure to earthquake waves with a special focus on seismic hazard evaluation, mitigation of liquefaction, ground enhancement, foundation structure, and soil-structure interaction. Detailed in the review are the facts that ground conditions are a decisive factor in regulating the damage of an earthquake and that geotechnical precautions are necessary in minimizing seismic risk in city centres with high population density. The synthesized results indicate that the seismic requirement of cities may change by 2-4 times between the different micro zones of the city because of the variation of the local soil. Sites in the urban areas whose Vs30 values do not exceed 180 m/s are always linked to high ground amplification and vulnerability to liquefaction. Liquefaction mitigation measures have proven to be highly advantageous, with densification procedures reducing post-earthquake settlement by 30-50 %, drainage systems by 40-70 % of excess pore water pressure, and soil stabilization strategies offering up to 60-80 % settlement reduction. Ground improvement practices enhance stiffness on the soil by around 1.5-3 times, whereas the piles-raft foundation reduces seismic settlement by 20-40 relative to a shallow foundation. The importance of soil-structure interaction on seismic response and design requirements is taken into account by considering the effect on structural natural periods of 10-30%. Despite the systematic technical synthesis of the study, the results rely on published literature and not new experimental or numerical analysis, and thus constitute indicative ranges of performance as opposed to site-specific prediction. Future studies should be aimed at incorporating field studies, numerical models, and data-driven methods to improve such results. Additional effort should also be made on sustainable ground improvement materials and real-time monitoring systems in order to facilitate sustainable and resilient urban development. Generally, the research indicates that there is a need to incorporate geotechnical-based solutions in urban seismic planning to minimize the damage caused by earthquakes and enhance the post-earthquake operational activities.

REFERENCES

[1] Firoozi AA, Firoozi AA. Geotechnical innovations for seismic-resistant urban infrastructure. J. Civ. Eng. Urban. 2024;14(3):346-55. https://dx.doi.org/10.54203/jceu.2024.39

[2] Yenidogan C. Earthquake-resilient design of seismically isolated buildings: A review of technology. Vibration. 2021 Jul 22;4(3):602-47. https://doi.org/10.3390/vibration4030035

[3] Zheng G, Cheng XS, Zhou HZ, Zhang TQ, Yu XX, Diao Y, Wang RZ, Yi F, Zhang WB, Guo W. Resilient evaluation and control in geotechnical and underground engineering. China Civ. Eng. J. 2022; 55:1-38.

[4] Urlainis A, Shohet IM. A comprehensive approach to earthquake-resilient infrastructure: integrating maintenance with seismic fragility curves. Buildings. 2023 Sep 6;13(9):2265. https://doi.org/10.3390/buildings13092265

[5] Shareef SS. Earthquake consideration in architectural design: Guidelines for architects. Sustainability. 2023 Sep 15;15(18):13760. https://doi.org/10.3390/su151813760

[6] Sojobi AO, Liew KM. Multi-objective optimization of high-performance concrete columns under compressive loading with potential applications for sustainable earthquake-resilient structures and infrastructures. Composite Structures. 2023 Jul 1; 315:117007. https://doi.org/10.1016/j.compstruct.2023.117007

[7] Qian, Z. H., Yuan, J. S., Shi, J., & Cao, X. Y. (2025). Recent Developments and Innovations in Resilient Infrastructure: Exploring Cutting-Edge Strategies, Technologies, and Practices. Buildings, 15(5), 792. https://doi.org/10.3390/buildings15050792

[8] Papatheodorou K, Theodoulidis N, Klimis N, Zulfikar C, Vintila D, Cardanet V, Kirtas E, Toma-Danila D, Margaris B, Fahjan Y, Panagopoulos G. Rapid earthquake damage assessment and education to improve earthquake response efficiency and community resilience. Sustainability. 2023 Dec 6;15(24):16603. https://doi.org/10.3390/su152416603

[9] Rezvani SM, Falcão Silva MJ, de Almeida NM. The Risk-Informed Asset-Centric (RIACT) Urban Resilience Enhancement Process: An outline and pilot-case demonstrator for earthquake risk mitigation in portuguese municipalities. Applied Sciences. 2024 Jan 11;14(2):634. https://doi.org/10.3390/app14020634

[10] Al-Janabi MA, Al-Jeznawi D, Yang TY, Bernardo LF, Andrade JM. Enhancing Structural Resilience for Sustainable Infrastructure: A global review of seismic isolation and energy dissipation practices. Sustainability. 2025 Aug 13;17(16):7314. https://doi.org/10.3390/su17167314

[11] Jamil T. Improved approaches in civil engineering for earthquake-resilient infrastructure in pakistan. Pakistan Journal of Science, Engineering, and Modern Research. 2023 Jun 30;3(1):123-50. https://doi.org/10.71465/pjsemr15

[12] Anastasiadis A, Mosoarca M. Earthquake resilient near zero energy buildings: attributes and perspectives. Sustainability. 2024 Mar 11;16(6):2317. https://doi.org/10.3390/su16062317

[13] Hore S, Alim MA, Hore R. Impact of Earthquakes on Soil Chemical Properties: A Review of Mechanisms, Changes, and Implications for Environmental and Structural Resilience. Earthquake. 2025;3(1):8575. https://doi.org/10.59429/ear.v3i1.8575

[14] Zhang Y, Fung JF, Cook D, Johnson KJ, Sattar S. Benefit–Cost Analysis for Earthquake-Resilient Building Design and Retrofit: State of the Art and Future Research Needs. Natural hazards review. 2024 Aug 1;25(3):03124001. https://doi.org/10.1061/NHREFO.NHENG-1910

[15] Singh SV, Ghani S. A smarter approach to liquefaction risk: harnessing dynamic cone penetration test data and machine learning for safer infrastructure. Frontiers in Built Environment. 2024 Oct 25; 10:1495472. https://doi.org/10.3389/fbuil.2024.1495472

[16] Putri MZ, Mase LZ, Amri K, Misliniyati R, Hardiansyah H, Refrizon R. Geospatial Modeling of Soil Plasticity Index and Water Content Distribution in Coastal Bengkulu: A Basis for Resilient Infrastructure Planning. Journal Innovation of Civil Engineering (JICE). 2025 Jul 7;6(1):1-1.

[17] Najar IA, Ahmadi R. Editorial scope: Geotechnical earthquake engineering edition. J. Civ. Eng. Sci. Technol. 2023 Sep;14(2):78-82. https://doi.org/10.33736/jcest.6006.2023

[18] Fayaz M, Romshoo SA, Rashid I, Chandra R. Earthquake vulnerability assessment of the built environment in the city of Srinagar, Kashmir Himalaya, using a geographic information system. Natural Hazards and Earth System Sciences. 2023 Apr 27;23(4):1593-611. https://doi.org/10.5194/nhess-23-1593-2023

[19] Sadikoglu E, Demirkesen S, Dal O, Seker O, Nowak P, Toprak S. Fostering Sustainability and Resilience in Engineering Education and Practice: Lessons Learnt from the 2023 Kahramanmaras Earthquakes. Sustainability. 2025 Feb 11;17(4):1470. https://doi.org/10.3390/su17041470

[20] Wilding AJ, Luna R. GIS-based geotechnical seismic hazard screening tool. InProceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4) 2009 (pp. 2675-2678). IOS Press. https://doi.org/10.3233/978-1-60750-031-5-2675