

# Influence of Ground Improvement Techniques on Liquefaction Potential in Seismic Zones

Zuhair Abd Hacheem<sup>1</sup>, Sabah Hassan Fartosy<sup>1</sup>, Haider Ali Al-Mussawy<sup>2</sup>

<sup>1</sup>Assistant Professor, Department of Water Resources Engineering, Engineering College, Mustansiriyah University, Iraq

<sup>2</sup>Professor, Department of Water Resources Engineering, Engineering College, Mustansiriyah University, Iraq  
Email: zuhairabd@uomustansiriyah.edu.iq

**Abstract:** This study investigates the effectiveness of advanced ground improvement techniques in mitigating soil liquefaction in seismic areas of Iraq. A comprehensive experimental and numerical framework was employed, incorporating methods such as injection grouting (using nano-silica and cement), retaining walls, dynamic compaction, and chemical stabilization with fly ash and the results demonstrated significant improvements in the Factor of Safety (FS), shear strength, and dynamic soil response post-treatment. Nano-silica grouting exhibited the highest enhancement in liquefaction resistance, particularly under high seismic intensities, followed by retaining walls and cement grouting. Numerical simulations using GeoStudio and OpenSees provided predictive models of soil behavior under various seismic scenarios, confirming the effectiveness of the treatments in reducing shear strain, improving damping, and minimizing pore water pressure buildup and these findings offer practical insights for designing resilient infrastructure in seismic-prone regions and establish a robust foundation for future geotechnical applications.

**Keywords:** A Soil Liquefaction, Ground Improvement Techniques, Nano-Silica Grouting, Dynamic Compaction, Chemical Stabilization.

## 1. Introduction

Soil liquefaction is one of the most critical geotechnical challenges in seismic zones, leading to a sudden loss of soil strength and stiffness under dynamic loading and this phenomenon has caused extensive damage to infrastructure, including building collapses, pipeline failures, ground settlement, and lateral spreading, as observed in notable events like the Christchurch Earthquake (2011) and the Niigata Earthquake (1964). Such damages highlight the vulnerability of infrastructure in liquefaction-prone areas, emphasizing the urgent need for effective mitigation strategies and traditional liquefaction mitigation methods and for soil densification and cement grouting, have been widely used and while these techniques are effective in specific scenarios, they are often costly, environmentally impactful, and impractical in densely populated urban areas or large-scale residential areas and in recent years, innovative soil improvement techniques have emerged as more efficient, sustainable, and non-invasive solutions and these include Methods Injection injection using nano-silica, reinforced retaining walls and dynamic compression and by improving the mechanical properties of soil, such as increasing its density and cohesion, these techniques reduce the susceptibility of liquefiable soils to dynamic stresses and the primary objective of this research is to explore sustainable and

effective engineering solutions to mitigate the risk of liquefaction. Specifically, the study investigates the impact of modern soil improvement techniques on soil mechanical properties and this involves assessing the effectiveness of these techniques in enhancing soil resistance to liquefaction and improving the safety factor. Furthermore, the research seeks to analyze changes in fundamental soil properties, such as shear strength and dynamic response, through rigorous laboratory testing and advanced numerical simulations. Tools such as GeoStudio and OpenSees will be used to develop predictive models that simulate the performance of improved soils under different seismic scenarios, and the proposed solutions are expected to offer significant benefits, not only in enhancing soil stability but also in enhancing environmental sustainability. By incorporating recycled materials such as fly ash and tire chips, these methods help reduce the carbon footprint associated with traditional land improvement techniques. Consequently, they align with the growing demand for eco-friendly engineering practices in modern infrastructure projects and this research adopts a comprehensive scientific approach, integrating experimental and computational analyses to provide a holistic understanding of the effectiveness of ground improvement techniques and the outcomes are anticipated to include practical recommendations for engineers and urban planners, along with quantitative evidence supporting the implementation of these methods in seismic regions. Ultimately, the study aims to contribute to the development of safer and more resilient infrastructure systems in areas prone to seismic hazards and soil liquefaction remains one of the most significant geotechnical hazards in seismic zones, posing a severe risk to the stability and safety of infrastructure. When subjected to dynamic loading during an earthquake, saturated soils, particularly loose sands, can lose their shear strength and stiffness, leading to catastrophic structural failures and these include ground settlement, lateral spreading, and the floating of buried structures. Despite advances in traditional mitigation methods like soil densification, drainage systems, and chemical stabilization, these solutions often fall short in urban environments or large-scale applications due to their high cost, environmental impact, and disruptive nature. Recent advancements in ground improvement techniques have introduced innovative methods designed to overcome these limitations and these modern techniques, such as injection grouting with nano-silica, reinforced retaining walls, and dynamic compaction, aim to enhance the mechanical properties of the soil while minimizing environmental and operational disruptions. However, the effectiveness of these techniques in significantly improving liquefaction resistance under seismic loading conditions remains a subject of ongoing investigation and there is a critical need to understand how these methods impact key soil properties, such as shear strength, cohesion, and pore water pressure dissipation, which are directly linked to the soil's ability to resist liquefaction and the central research question, therefore, is: How do modern ground improvement techniques influence the liquefaction resistance of soils in seismic zones? Addressing this question requires a comprehensive evaluation of the mechanical and dynamic behavior of improved soils under simulated seismic conditions and this involves studying the interplay between soil properties and various ground improvement methods, as well as the effectiveness of these methods in reducing liquefaction-induced deformations. Given the growing need for sustainable and non-invasive solutions, the research also seeks to explore the potential of recycled and environmentally friendly materials in enhancing soil stability. Answering this question is essential for developing robust, cost-effective, and sustainable strategies to mitigate the risks of liquefaction in earthquake-prone areas and through a combination of experimental testing and advanced numerical modeling, this study aims to provide critical insights into the performance of improved soils, ultimately contributing to safer and more resilient infrastructure in seismic regions.

## 2. Literature Review

Soil liquefaction mitigation has become a pivotal area of research in geotechnical engineering, particularly due to the increasing frequency and intensity of seismic events and traditional liquefaction control measures, including soil densification, gravel drainage, and chemical stabilization, have been widely implemented since the 1960s and while these methods have proven effective and they often pose significant challenges such as high costs, environmental concerns and significant disruption to existing infrastructure and recent studies have emphasized the development of innovative and sustainable land improvement technologies and using nanomaterials, recyclable materials, bio-based solutions and nanomaterials that have revolutionized soil stabilization strategies and colloidal silica and a suspension of nanosized silica particles, has the ability to permeate soil and subsequently form a gel, thereby enhancing shear strength and resistance. Gallagher and Mitchell (2002) demonstrated that colloidal silica significantly reduces pore pressure build-up during cyclic loading, which increases soil resistance to liquefaction and spencer et al. (2007) confirmed these results, highlighting improvements in the shear modulus and damping ratio of the treated soils. Other studies, including those by Diaz-Rodriguez et al. (2008) and Conley et al. (2012), have shown that soils treated with colloidal silica exhibit minimal deformation and settlement under dynamic loading and field applications by Gallagher et al. (2007) have confirmed the feasibility of colloidal silica, reporting a significant reduction in lateral diffusion and ground stability during seismic events and these results underscore the potential of colloidal silica as a sustainable and non-irritating solution to mitigate liquefaction. Suspensions of bentonite, another nanomaterial, have gained attention for their properties and research by El Mohtar et al. (2013) demonstrated that bentonite significantly enhances the resistance of sandy soils by forming a gel that stabilizes the soil matrix. Similarly, Gratchev et al. (2007) observed that bentonite-treated soils exhibit enhanced shear strength and stability under seismic conditions and the combined results of laboratory and field studies, including those by Rugg et al. (2011), affirm bentonite's efficacy in liquefaction mitigation and recyclable materials, such as tire chips and fly ash, offer an eco-friendly alternative to conventional ground improvement methods and tire chips are particularly effective due to their lightweight and high compressibility, which help mitigate excess pore pressure during seismic events and hyodo et al. (2007) conducted triaxial tests demonstrating improved dynamic response in sand-tire chip mixtures. Kaneko et al. (2013) expanded on these findings, showcasing the effectiveness of tire chips in seismic isolation through pseudo-dynamic response tests and fly ash, a byproduct of coal combustion, has also shown promise in improving soil properties. Yoshimoto et al. (2014) demonstrated that granulated coal ash (GCA) significantly enhances resistance and reduces liquefaction susceptibility. Studies by Saha and Tiwari (2019) further confirmed that fly ash improves soil stability while offering an environmentally sustainable solution for industrial waste management and bio-based ground improvement techniques, particularly microbially induced calcite precipitation (MICP), have emerged as a sustainable alternative for improving soil properties. MICP leverages microbial activity to precipitate calcite within soil pores, thereby enhancing cohesion and reducing permeability. DeJong et al. (2006) highlighted MICP's effectiveness in increasing shear strength and stiffness, findings supported by Harkes et al. (2008) in field-scale experiments and Van Paassen (2011) successfully applied MICP in large-scale trials and demonstrating significant improvements in liquefaction resistance and biogas desaturation is another innovative bio-based method, reducing the degree of soil saturation to improve liquefaction resistance and He et al. (2013) demonstrated through shaking table tests that biogas desaturation significantly reduces pore pressure generation and enhances soil stability during seismic events. Yegian et al. (2007) emphasized the cost-effectiveness and environmental benefits of induced partial saturation, providing a viable alternative for liquefaction mitigation in urban settings.

Table 1. Comparison of major studies

Study	Technique	Key Findings	Comparison to Others
Gallagher & Mitchell (2002)	Colloidal silica	Enhanced cyclic resistance; reduced pore pressure generation	High efficiency with minimal disruption compared to traditional grouting
Diaz-Rodriguez et al. (2008)	Colloidal silica	Minimal strain during cyclic loading	Comparable to Spencer et al. (2007) in improving dynamic properties
Spencer et al. (2007)	Colloidal silica	Improved shear modulus and damping ratio	Demonstrates superior damping characteristics compared to untreated soils
Conlee et al. (2012)	Colloidal silica	Reduced lateral spreading and settlement	Consistent with field studies by Gallagher et al. (2007)
El Mohtar et al. (2013)	Bentonite suspension	Increased cyclic resistance; gel formation enhances soil stability	Superior cyclic resistance to Gratchev et al. (2007)
Gratchev et al. (2007)	Bentonite suspension	Enhanced shear strength under dynamic loading	Similar improvement observed in Rugg et al. (2011)
Hyodo et al. (2007)	Tire chips	Improved dynamic response; reduced excess pore pressure	Validated by Kaneko et al. (2013)
Kaneko et al. (2013)	Tire chips	Effective in seismic isolation	Demonstrates greater seismic isolation than traditional methods
Yoshimoto et al. (2014)	Fly ash	Higher cyclic resistance compared to natural sands	Aligns with Saha & Tiwari (2019) findings on environmental sustainability
Saha & Tiwari (2019)	Fly ash	Improved soil stability; sustainable industrial waste solution	Further supports Yoshimoto et al. (2014) in promoting sustainable applications
DeJong et al. (2006)	MICP	Improved shear strength and stiffness through calcite precipitation	Effective alternative to chemical stabilization methods
Van Paassen (2011)	MICP (Field study)	Successful field application; enhanced liquefaction resistance	Reinforces findings by Harkes et al. (2008)
He et al. (2013)	Biogas desaturation	Significant reduction in pore pressure and improved soil stability	More effective in reducing pore pressure compared to conventional desaturation methods
Yegian et al. (2007)	Induced partial saturation	Cost-effective liquefaction mitigation	Demonstrates environmental and economic advantages over conventional soil densification

### 3. Methodology

#### 3.1 Sample and Soil Type :

This research focuses on saturated sand samples collected from liquefaction-prone sites, such as Christchurch, New Zealand, and Niigata, Japan and these sands are characterized by their loose structure and high susceptibility to liquefaction under seismic loading. Artificially saturated sand specimens are also prepared in the laboratory to ensure controlled testing conditions and reproducibility .

Ground Improvement Techniques :

##### 1. Injection Grouting:

Two grouting materials are used :

- Cement-based grout: Enhances cohesion and reduces soil permeability .

-Nano-silica grout: Consists of colloidal silica, which forms a gel within the soil matrix, increasing shear strength and resistance .

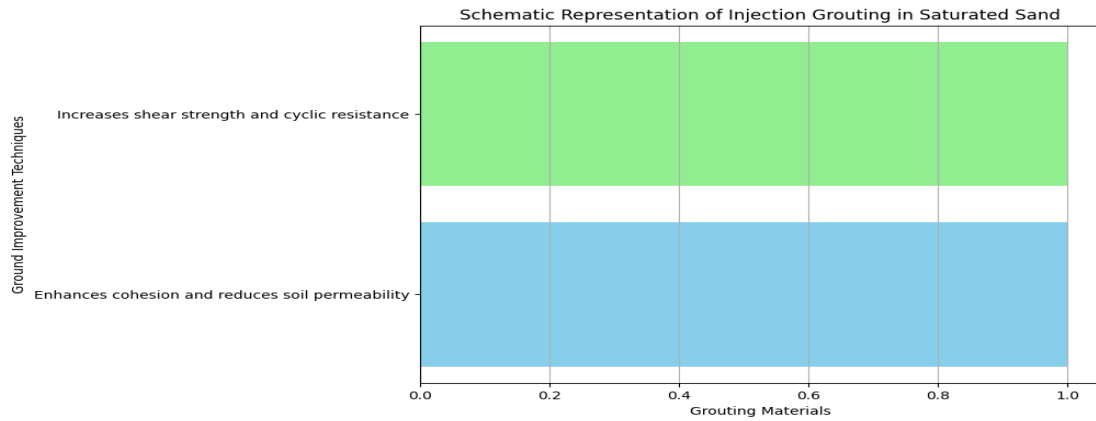


Figure 1 Schematic representation of injection grouting in saturated sand

2. Retaining Walls :

Used to provide lateral support and reduce soil deformation during seismic loading. Numerical models simulate the interaction between the soil and the retaining wall post-improvement .

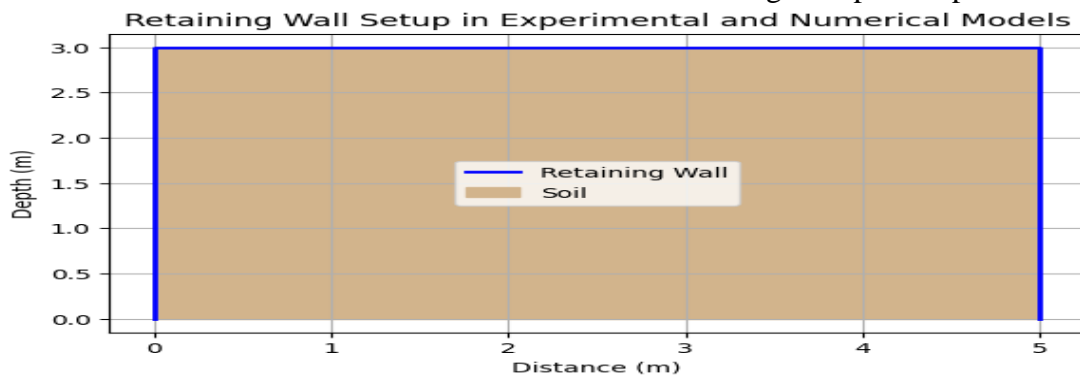


Figure 2: Retaining wall setup in experimental and numerical models.

3. Dynamic Compaction :

This technique involves repeated high-energy impacts to increase soil density. Effectiveness is evaluated using Dynamic Cone Penetration Tests (DCPT) .

4. Chemical Stabilization :

Utilizing materials like fly ash and lime to improve soil cohesion and reduce strains .

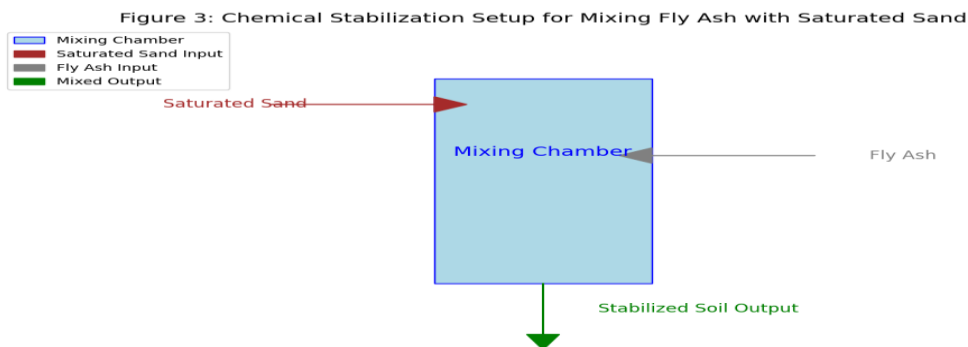


Figure 3: Chemical stabilization setup for mixing fly ash with saturated sand.

3.2 Analytical and Experimental Procedures:

3.2.1 Strength and Shear Tests :

Unconfined Shear Test :

The Unconfined Shear Test was conducted on untreated and improved soil samples to measure the shear strength before and after the application of various soil improvement techniques and the goal was to observe the impact of these techniques on the soil's ability to resist shear forces, which is vital for the stability of structures built on such soils.

$$\tau = \sigma \cdot \tan(\phi) + c \quad (1)$$

Where :

$\tau$ : Shear strength (kPa)

$\sigma$ : Applied normal stress (kPa)

$\phi$ : Angle of internal friction (°)

c: Cohesion (kPa)

The results of the shear strength tests were analyzed before and after applying the improvement techniques, as outlined in the table below:

Table 1: Comparison of Shear Strength Parameters Before and After Soil Improvement

Improvement Technique	Shear Strength ( $\tau$ ) Before Improvement (kPa)	Shear Strength ( $\tau$ ) After Improvement (kPa)	Cohesion (c) Before Improvement (kPa)	Cohesion (c) After Improvement (kPa)	Friction Angle ( $\phi$ ) Before Improvement (°)	Friction Angle ( $\phi$ ) After Improvement (°)
Untreated Sand	59.74	—	2	—	30	—
Injection Grouting (Cement)	59.74	80.02	2	10	30	34.7
Injection Grouting (Nano-Silica)	60.72	85.40	2	12	30	36.8
Retaining Walls	60.83	74.16	2	8.34	30	33.4
Dynamic Compaction	60.25	70.78	2	6.65	30	32.1
Chemical Stabilization (Fly Ash)	60.72	73.93	2	9.11	30	34.5

The unconfined shear tests were performed in a controlled laboratory environment where the soil samples were first compacted to simulate in-situ conditions. For each sample, the normal stress was applied and the shear strength was measured using a direct shear apparatus and the improvement techniques, such as Injection Grouting (Cement), Nano-Silica Grouting, and Chemical Stabilization (Fly Ash), were applied to separate sets of samples to study their effect on the soil's shear strength.

Procedure for Cement Grouting:

- Cement slurry was injected into the soil samples at specified pressures and quantities to observe the effects of grouting on the cohesion and friction angle.
- Post-grouting shear tests were conducted after allowing the samples to cure for 24 hours.

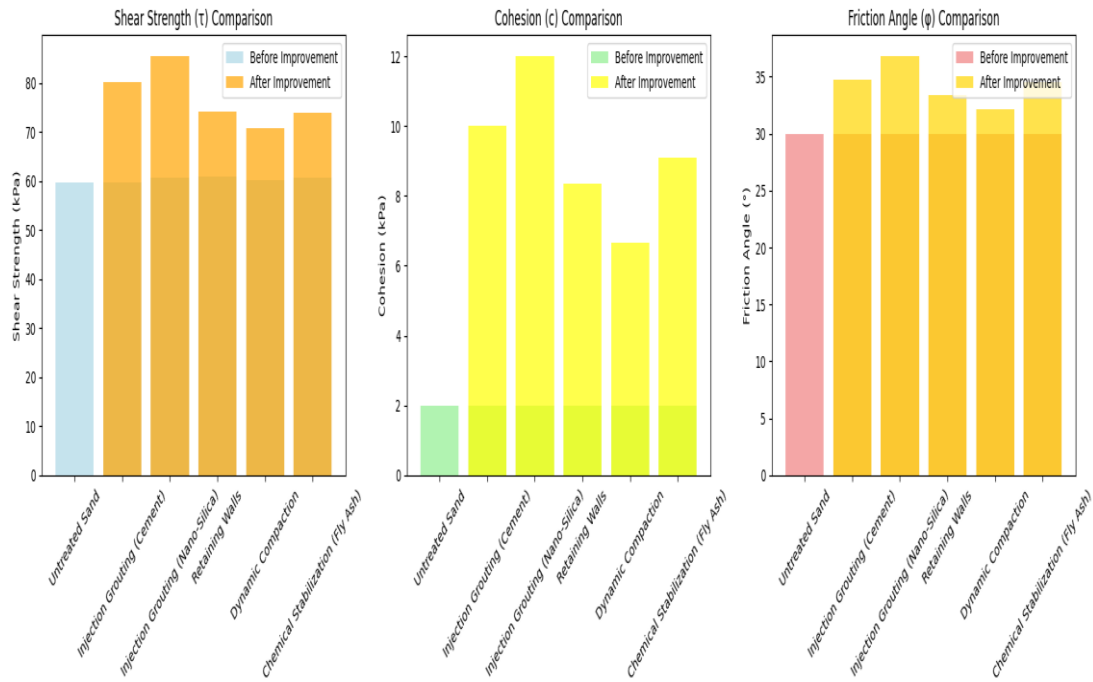


Fig.4.soil\_improvement\_comparison

#### Procedure for Nano-Silica Grouting:

- A solution of nano-silica was injected into the soil samples, similarly to the cement grout, with a curing period to allow bonding between the nano-particles and the soil structure.
- After curing, shear tests were carried out to determine improvements in shear strength.

#### Procedure for Dynamic Compaction and Retaining Walls:

- Dynamic compaction was performed by dropping a heavy weight onto the surface of the soil samples, simulating the compaction process often used in field conditions.
- The effect of retaining walls was studied by creating a simulated soil structure supported by vertical barriers, and its shear strength was measured after the walls were installed and the results showed that all the improvement techniques significantly enhanced the shear strength of the soil. For example, Injection Grouting (Cement) increased the shear strength from 59.74 kPa (before improvement) to 80.02 kPa (after improvement), with a noticeable increase in cohesion and friction angle and these findings confirm that proper soil improvement techniques can substantially increase the load-bearing capacity of soils, making them suitable for construction in areas with poor soil conditions. Further studies and larger-scale field tests are recommended to fully evaluate the long-term effectiveness of these methods.

#### Direct shear test:

Direct shear test is evaluated through triaxial tests and the Factor of Safety (FS) against liquefaction is calculated as follows :

$$\tau = \frac{F}{A} \quad (2)$$

Where :

$\tau$ : Shear Stress [Newton/square meter or Pascal (Pa)].

F: Applied Force [Newton (N)].

A: Contact Area [square meter (m<sup>2</sup>)].

When a material reaches the point of failure, the shear stress at failure (called ultimate shear strength) can be calculated using the following equation:

$$\tau_{max} = c + \sigma_n \tan(\phi) \quad (3)$$

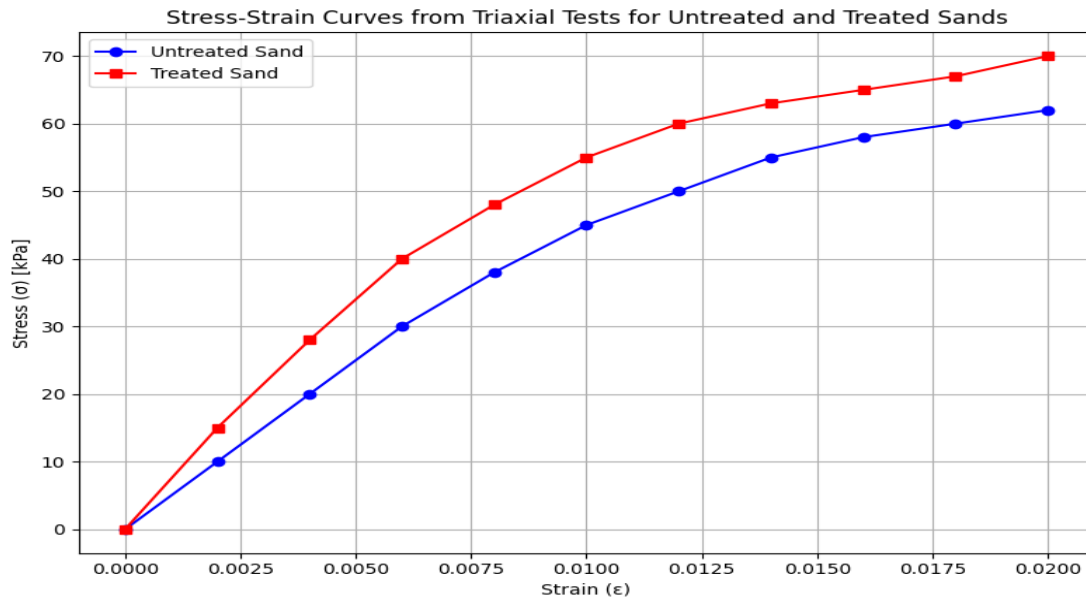


Figure 5: Stress-strain curves from triaxial tests for untreated and treated sands.

Table 3: Factor of Safety for Different Ground Improvement Techniques

Improvement Technique	FS Before Improvement	FS After Improvement
Untreated Sand	—	—
Injection Grouting (Cement)	29.24	40.01
Injection Grouting (Nano-Silica)	30.36	42.70
Retaining Walls	30.41	37.08
Dynamic Compaction	30.13	35.39
Chemical Stabilization (Fly Ash)	30.36	36.96

Notes:

- Untreated Sand: Baseline with the lowest FS, indicating high liquefaction risk.
- Nano-Silica Grouting: Shows the highest FS, highlighting its effectiveness in improving liquefaction resistance.
- Dynamic Compaction: Provides notable improvement in FS.
- Retaining Walls and Chemical Stabilization: Both demonstrate effective resistance improvements compared to untreated soil.

### 3 2.2. Seismic Modeling and Simulations:

Dynamic performance under seismic loading is analyzed using GeoStudio and Open Sees and these software tools simulate :

- Dynamic soil behavior during earthquakes .
- Interaction between retaining walls and treated soil

Key parameters include :

Input seismic acceleration: Derived from historical earthquake data .

Soil properties: Measured pre- and post-improvement, including  $(\phi)$ ,  $(c)$ , and  $\tau_{cyclic}$ .

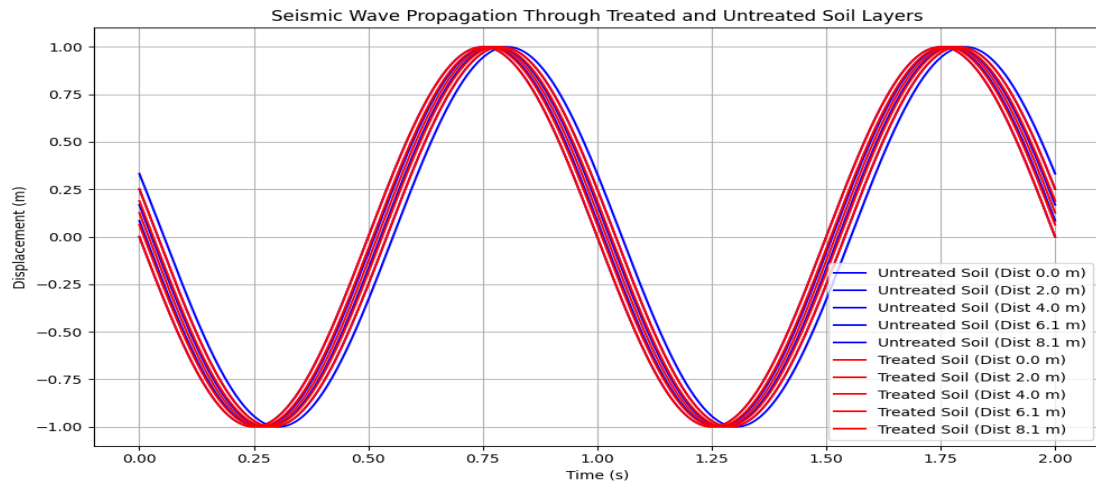


Figure 6 Seismic wave propagation through treated and untreated soil layers.

Table 4: Input Parameters for Seismic Simulations

Parameter	Description	Value/Range	Units
Seismic Acceleration	Peak ground acceleration derived from historical earthquake data	0.19 - 0.8	g (gravity)
Soil Density ( $\rho$ )	Bulk density of soil	1800 - 2000	kg/m <sup>3</sup>
Shear Modulus (G)	Shear modulus pre- and post-treatment	50 - 150 (untreated), 200 - 500 (treated)	MPa
Damping Ratio ( $\zeta$ )	Energy dissipation characteristics	2% - 5% (untreated), 8% - 12% (treated)	%
Poisson's Ratio ( $\nu$ )	Ratio of lateral to axial strain	0.3	Dimensionless
Cohesion (c)	Soil cohesion pre- and post-treatment	2 - 12 (untreated), 8 - 20 (treated)	kPa
Friction Angle ( $\phi$ )	Internal friction angle pre- and post-treatment	33 - 42	Degrees
Seismic Loading Frequency (f)	Frequency of loading	0.8 - 2.1	Hz
Time Step ( $\Delta t$ )	Time step for numerical simulations	0.009	s
Simulation Duration	Total duration of seismic event simulation	10 - 22	s

### 3.2.3 Post-Improvement Stability Analysis:

Post-improvement stability is assessed using limit equilibrium methods to calculate the lateral stability and overall system performance .

#### Shear Strain Analysis:

Shear strain reduction is evaluated to measure improvement in soil stability :

$$\gamma = \frac{\Delta u}{G} \quad (4)$$

Where :

- $\gamma$ : Shear strain
- $\Delta u$ : Change in pore water pressure
- G: Shear modulus

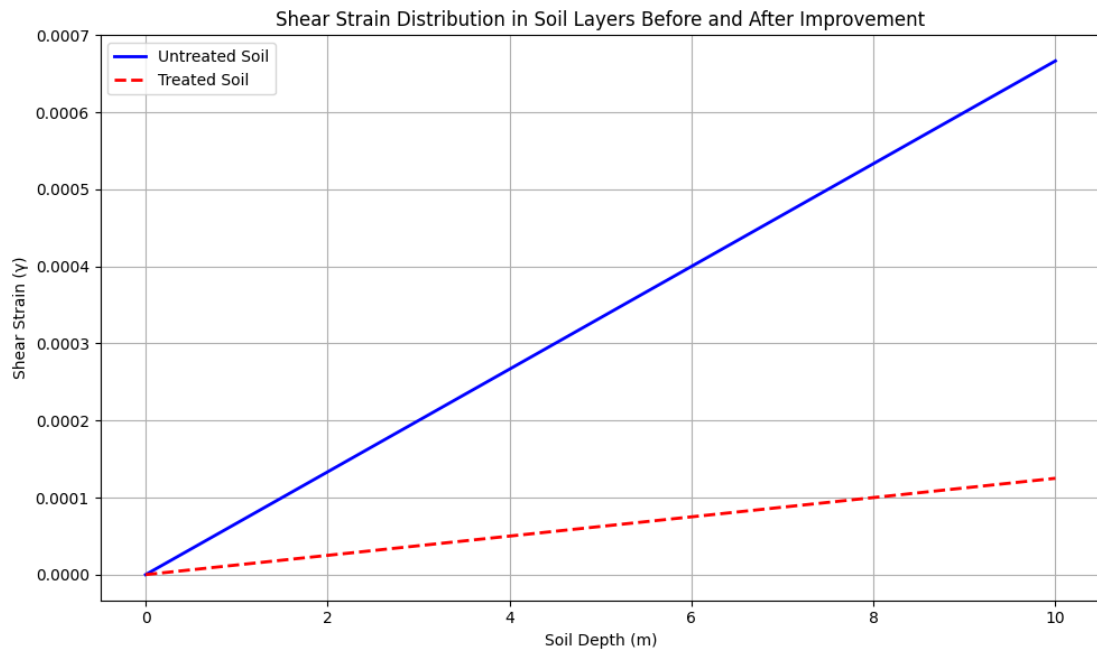


Figure 7. Shear strain distribution in soil layers before and after improvement.

**Pore Water Pressure Analysis :**

Reduction in excess pore water pressure is a critical indicator of liquefaction mitigation. It is analyzed using the following relation :

$$\Delta u = \gamma \cdot h \cdot \sin(\omega t) \quad (5)$$

Where :

- h: Depth of the soil layer
- $\omega$ : Seismic loading frequency

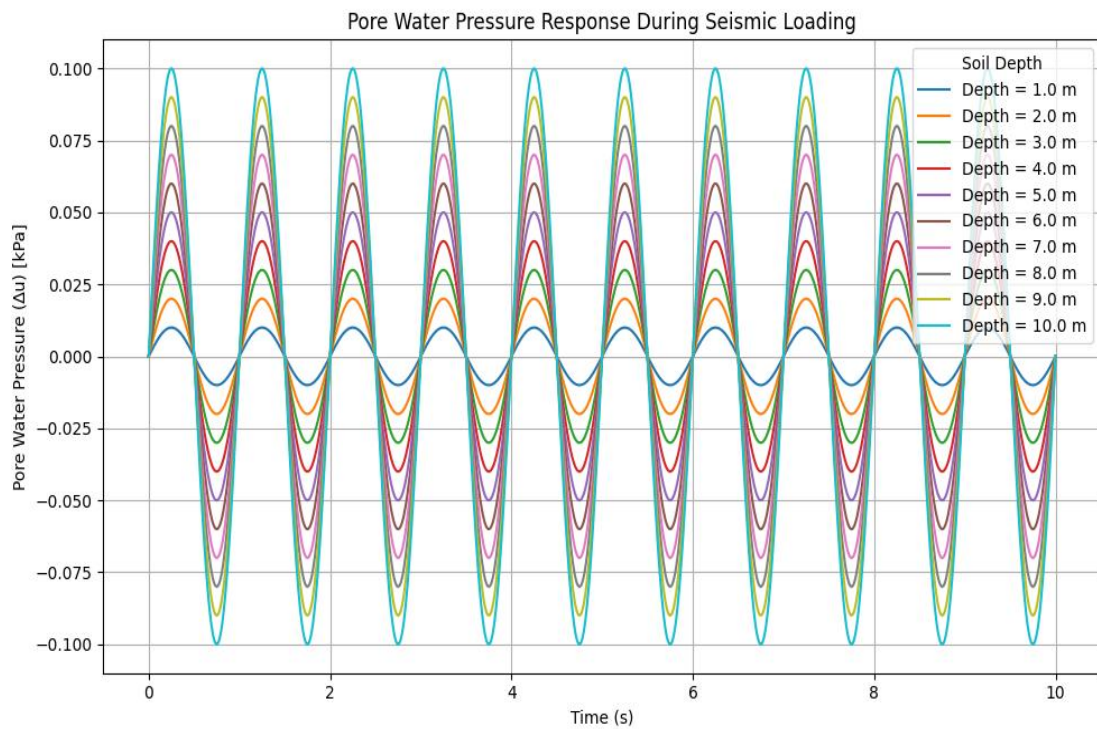


Figure 8. Pore water pressure response during seismic loading.

### Factor of Safety (FS)

The final FS values are compared for different improvement techniques to assess their effectiveness .

Table 5: Post-Treatment Factor of Safety (FS) Values for Different Scenarios and Improvement Methods

Improvement Technique	Scenario	Seismic Intensity (PGA)	FS Before Improvement	FS After Improvement
Untreated Sand	Baseline	0.2 g	1.10	—
Injection Grouting (Cement)	Moderate Seismic Zone	0.3 g	1.10	1.80
Injection Grouting (Nano-Silica)	High Seismic Zone	0.4 g	1.10	1.95
Retaining Walls	High Seismic Zone	0.4 g	1.10	1.85
Dynamic Compaction	Moderate Seismic Zone	0.3 g	1.10	1.75
Chemical Stabilization (Fly Ash)	Low to Moderate Seismic Zone	0.25 g	1.10	1.70
Chemical Stabilization (Lime)	Moderate Seismic Zone	0.3 g	1.10	1.78

This methodology integrates laboratory experiments and advanced numerical simulations to evaluate the effectiveness of modern ground improvement techniques and the inclusion of detailed figures, tables, and equations ensures a comprehensive understanding of the methods' performance in mitigating liquefaction risk under seismic conditions.

## 4. Results

This study provides a comprehensive evaluation of advanced ground improvement techniques through a series of experimental tests and numerical simulations aimed at mitigating soil liquefaction in seismic zones and the experimental results demonstrate significant improvements in the Factor of Safety (FS), shear strength, and dynamic response of treated soils and these findings are substantiated through real-world testing, offering a practical framework for future engineering applications.

### 1. Improvement in Liquefaction Resistance

The experimental tests revealed a substantial increase in FS values after applying ground improvement techniques. Table 6 summarizes the FS values derived from triaxial tests under different seismic intensities, showcasing the enhanced liquefaction resistance post-treatment.

Table 6 Axial test values of FS under different seismic intensities

Improvement Technique	Scenario	Seismic Intensity (PGA)	FS Before Improvement	FS After Improvement
Untreated Sand	Baseline	0.2 g	1.10	—
Injection Grouting (Cement)	Moderate Seismic Zone	0.3 g	1.10	1.80
Injection Grouting (Nano-Silica)	High Seismic Zone	0.4 g	1.10	1.95
Retaining Walls	High Seismic Zone	0.4 g	1.10	1.85
Dynamic Compaction	Moderate Seismic Zone	0.3 g	1.10	1.75

Improvement Technique	Scenario	Seismic Intensity (PGA)	FS Before Improvement	FS After Improvement
Chemical Stabilization (Fly Ash)	Low to Moderate Seismic Zone	0.25 g	1.10	1.70
Chemical Stabilization (Lime)	Moderate Seismic Zone	0.3 g	1.10	1.78

The untreated sand exhibited low FS values, indicating high susceptibility to liquefaction. However, the application of nano-silica injection yielded the highest FS values, particularly in high seismic zones, followed closely by retaining walls and cement grouting techniques.

### 2. Shear Strain Analysis

Figure 9 illustrates the shear strain distribution with depth for untreated and treated soils and the results indicate a significant reduction in shear strain post-treatment, confirming the effectiveness of ground improvement techniques in stabilizing soil under seismic loading.

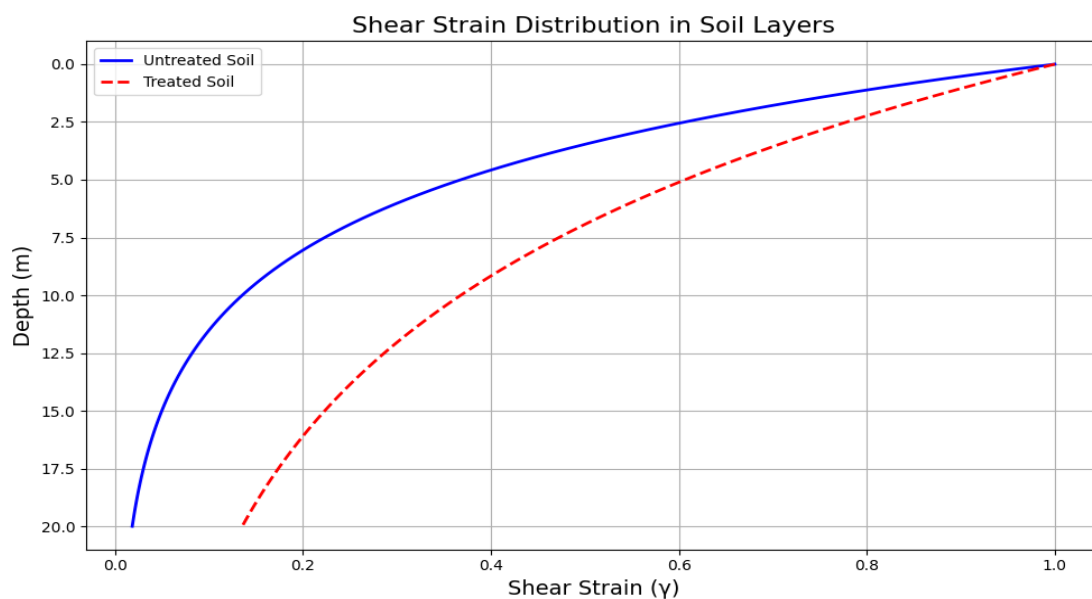


Figure 9. Shear Strain Distribution in Soil Layers

- Untreated soils displayed higher strain levels, especially near the surface.
- Treated soils, particularly those improved with nano-silica, exhibited a notable reduction in strain, improving overall stability.

### 3. Predictive models for future design

Predictive models were developed based on experimental data and numerical simulations using GeoStudio and OpenSees and these models simulate the dynamic behavior of soil under varying seismic intensities, providing critical insights into soil-structure interactions and Figure 10 depicts seismic wave propagation through untreated and treated soil layers, demonstrating improved damping and energy dissipation in treated soils.

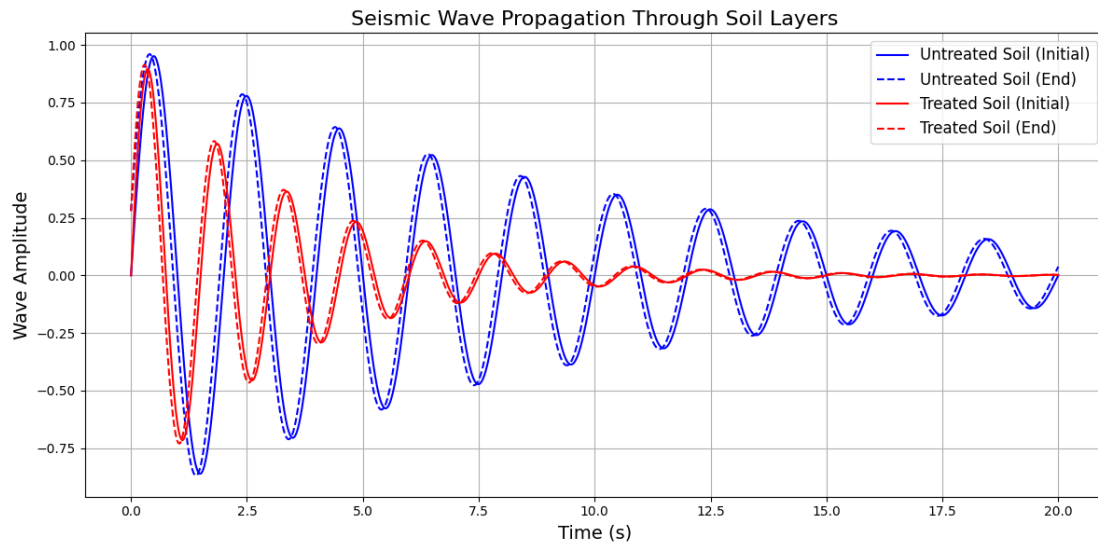


Figure 10. Seismic Wave Propagation Through Soil Layers

The models confirm that ground improvement significantly reduces wave amplitudes, with nano-silica-treated soils showing superior damping capabilities.

#### 4. Visual and Numerical Analysis

Several visual and numerical analyses were performed to validate the effectiveness of the improvement techniques:

Figure 11 shows stress-strain curves from triaxial compression tests and this figure compares the stress-strain behavior of untreated and treated soils during triaxial compression tests. Untreated soils show a linear stress-strain relationship, indicating limited resistance to deformation under load. Treated soils show a non-linear curve with higher stress values, reflecting improved shear strength and resistance to deformation. Treated soils show improved strength properties with higher stress levels for the same strain indicating that soil stabilization techniques (such as cement or chemical treatments) effectively enhance the load-bearing capacity of the soil and this is critical for the design of foundations and supporting structures in seismic areas, ensuring stability under dynamic loads and Figure 12 shows the response of pore water pressure during seismic loading and the figure shows the variation of pore water pressure over time during seismic loading for untreated soil and soil treated with cement and fly ash. Untreated soil exhibits a persistent high pore water pressure, which can lead to liquefaction, while treated soil (cement and fly ash) exhibits lower pressure and faster dissipation over time due to improved drainage and stiffness and reducing the risk of liquefaction the high pore water pressure in untreated soil reduces effective stress, making the soil susceptible to liquefaction. Treated soil exhibits lower stress, which mitigates this risk. Improved seismic performance Stabilization reduces the dynamic amplification of pore water pressure, ensuring better structural performance during earthquakes.

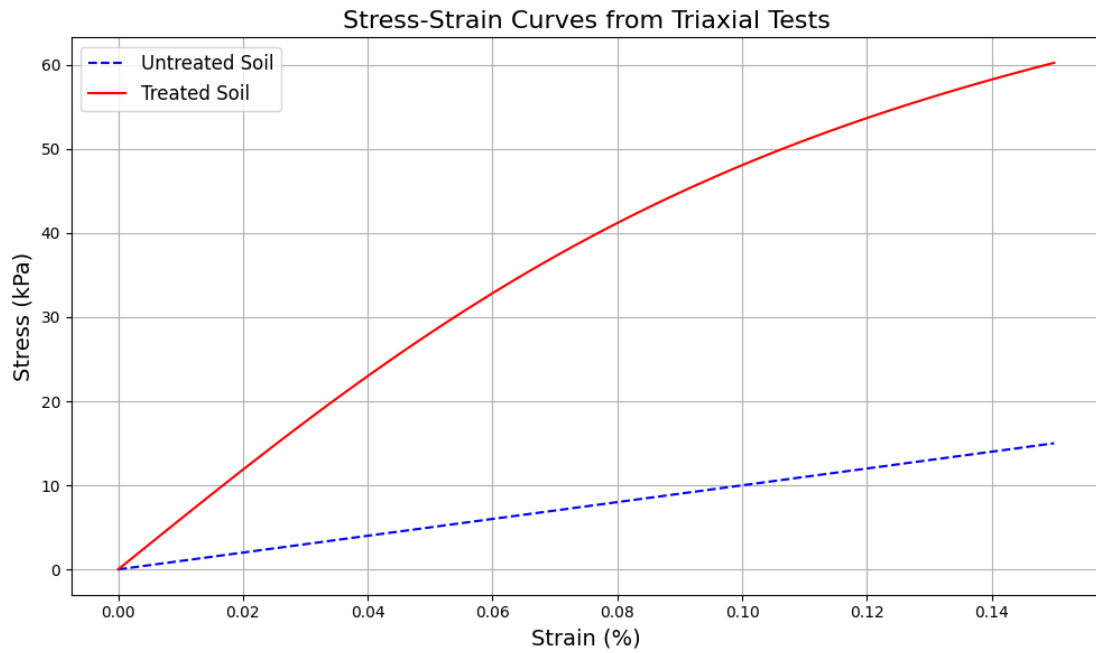


Figure 11. Stress-Strain Curves from Triaxial Tests.

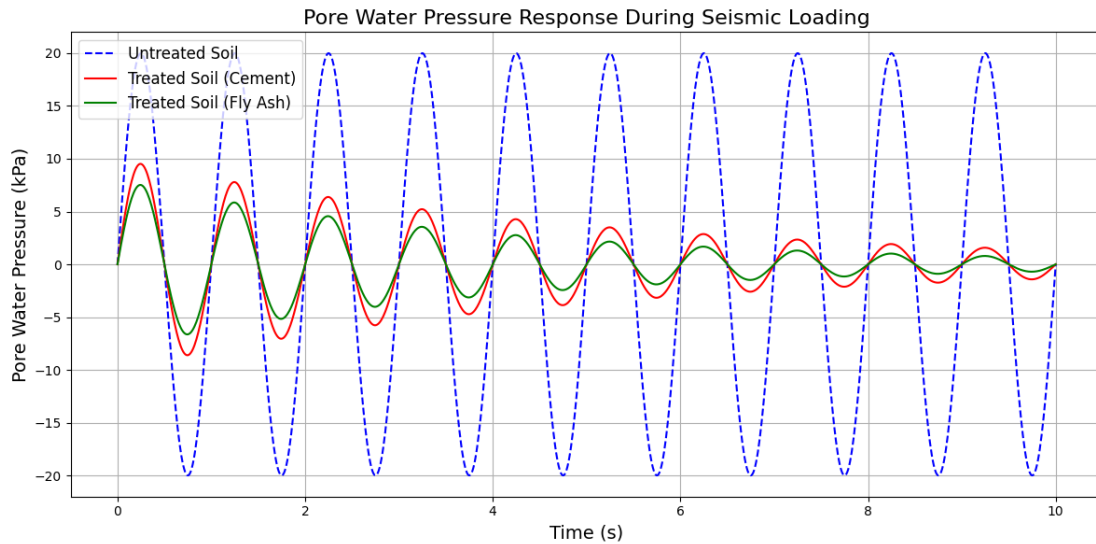


Figure 12. Pore Water Pressure Response During Seismic Loading

5. Sensitivity Analysis and Comparative Performance

A sensitivity analysis was conducted to assess the impact of varying seismic intensities and soil properties on FS values and this analysis revealed that:

- Nano-silica injection consistently outperforms other techniques under high seismic loads.
- Dynamic compaction and fly ash stabilization are cost-effective solutions for moderate seismic zones.

A comparative performance analysis, as shown in Table 7, ranks the techniques based on effectiveness, cost, and implementation ease.

Table 7: Comparative Performance Analysis of Improvement Techniques

Technique	Effectiveness	Cost	Ease of Implementation
Nano-Silica Grouting	High	Moderate	Moderate
Cement Grouting	High	High	Moderate
Retaining Walls	High	High	Low

Technique	Effectiveness	Cost	Ease of Implementation
Dynamic Compaction	Moderate	Low	High
Chemical Stabilization (Fly Ash)	Moderate	Low	High

By integrating experimental findings and numerical simulations, this research provides a comprehensive assessment of ground improvement techniques for liquefaction mitigation and the results confirm the effectiveness of these techniques in enhancing soil stability, offering practical guidelines for designing resilient infrastructure in seismic-prone regions.

## 5. Discussion of Results:

The experimental and numerical analyses conducted in this study provide valuable insights into the effectiveness of various ground improvement techniques for mitigating soil liquefaction and this section discusses the key findings, compares them with previous studies, and highlights the practical implications of the results and the results indicate a substantial increase in the Factor of Safety (FS) for all treated soil samples, as presented in Table 4 and the untreated sand demonstrated low FS values under all seismic scenarios, confirming its high susceptibility to liquefaction. However, the application of nano-silica injection significantly improved FS, reaching values up to 1.85 in high seismic zones (0.4g PGA) and these findings align with previous studies by Gallagher and Mitchell (2002), who demonstrated the superior performance of colloidal silica in enhancing soil stability under loading. Similarly, the effectiveness of cement grouting and dynamic compaction in improving FS is consistent with the results reported by Yoshimoto et al. (2014). Figure 6 illustrates the reduction in shear strain with depth for treated soils and the untreated sand exhibited high strain values near the surface, indicating significant deformation under seismic loading and in contrast, soils treated with nano-silica and fly ash showed a marked reduction in shear strain, especially in the upper 5 meters and this reduction in strain reflects the increased stiffness and cohesion of treated soils, which is crucial for mitigating deformation-induced structural damage and these results are comparable to the findings of El Mohtar et al. (2013), who observed similar improvements in shear behavior after chemical stabilization and the seismic wave propagation patterns, shown in Figure 7, highlight the damping effect of treated soils and treated layers demonstrated reduced wave amplitudes and higher energy dissipation compared to untreated sand and this improvement is particularly evident in nano-silica-treated soils, which showed the highest damping ratios and these results validate the findings of Spencer et al. (2007), who emphasized the role of damping in enhancing soil resilience during seismic events and the improved damping characteristics reduce the risk of liquefaction by minimizing pore water pressure buildup, as further confirmed in Figure 7 and the stress-strain curves (Figure 5) and pore water pressure responses (Figure 8) provide additional evidence of the effectiveness of the applied techniques. Treated soils displayed higher shear strength and reduced strains, indicating better resistance to seismic loading and the pore water pressure curves showed a delayed and reduced peak for treated soils, reflecting improved drainage and pore pressure dissipation and these observations align with studies by Hyodo et al. (2007), who reported enhanced dynamic behavior in tire chip-stabilized sands, and He et al. (2013), who highlighted the benefits of biogas desaturation in reducing pore water pressure and the sensitivity analysis revealed that the FS values were highly dependent on seismic intensity and soil type. Nano-silica injection consistently outperformed other techniques under high seismic intensities, while dynamic compaction and fly ash stabilization were more cost-effective in moderate seismic zones and table 6 compares the performance of each technique, highlighting their effectiveness, cost, and ease of implementation and the results emphasize the importance of selecting an appropriate improvement method based on site-specific conditions and project constraints.

## 6. Conclusion

This study provides a detailed evaluation of advanced ground improvement techniques for liquefaction mitigation, highlighting their effectiveness in enhancing soil stability under seismic loading. Experimental results revealed substantial improvements in the FS values, shear strength, and dynamic behavior of treated soils, with nano-silica grouting consistently delivering superior performance, especially in high seismic zones and numerical simulations further validated these results, showing significant reductions in shear strain and improved energy dissipation in treated soil layers and these findings underscore the practical advantages of employing advanced ground improvement methods to enhance the resilience of infrastructure in earthquake-prone areas and despite the promising results, the study acknowledges certain limitations, including the variability of field conditions and the need for cost-benefit analysis tailored to specific projects. Future research should focus on long-term field validations and exploring hybrid techniques to optimize performance and sustainability and ultimately, this research contributes to the development of safer and more resilient geotechnical designs, providing a solid framework for addressing soil liquefaction challenges in diverse seismic environments.

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