

Cite this article

Ahirwar P and Jain PK (2025)

Performance and challenges of stone columns for liquefaction mitigation: a comprehensive review.

Geotechnical Research **12**(4): 172–185,
<https://doi.org/10.1680/jgere.25.00003>

Research Article

Paper 2500003

Received 27/01/2025; Accepted 30/05/2025

Published with permission by Emerald Publishing Limited under the CC-BY 4.0 license.
(<http://creativecommons.org/licenses/by/4.0/>)

Geotechnical Research



Performance and challenges of stone columns for liquefaction mitigation: a comprehensive review

Priyanka Ahirwar

Civil Engineering Department, Maulana Azad National Institute of Technology, Bhopal, India (Orcid:0009-0001-5393-0637) (corresponding author: priyankamany98@gmail.com)

Pradeep Kumar Jain

Civil Engineering Department, Maulana Azad National Institute of Technology, Bhopal, India (Orcid:0000-0001-7962-8199)

Stone columns are an effective ground improvement technique for mitigating liquefaction hazards in seismically active regions. This review critically evaluates the mechanisms, applications, and limitations of stone columns through analysis of experimental studies, numerical simulations, and field case histories. The reinforcement effects of stone columns, including enhanced drainage, soil densification, and stress redistribution, are examined. Key design parameters influencing stone column efficacy, such as area replacement ratio and column spacing, are discussed. While stone columns have demonstrated potential in reducing liquefaction-induced deformations, their performance depends on site-specific conditions and design configurations. Challenges associated with stone column implementation, such as clogging and bulging failure under seismic loading, are assessed. Recent advancements in geosynthetic encasement technology show promise in enhancing column stability and drainage capacity. Future research priorities include the development of comprehensive design guidelines, establishment of performance databases, and validation of numerical models through collaborative efforts between researchers and practitioners. This review provides valuable insights to guide the optimisation of stone column technology for enhancing infrastructure resilience in earthquake-prone regions.

Keywords: geosynthetic encasement/ground improvement/liquefaction mitigation/seismic resilience/stone columns

Notation

A_s	stone column area
D	stone column diameter
D_r	relative density
e	void ratio
H	height of an embankment
L	length of the stone column
r_u	excess pore water pressure ratio
s	stone column spacing
s/d	spacing to diameter ratio
V_s	shear wave velocity
γ	unit weight of material
ϕ	angle of friction of the stone

Introduction

Earthquake-induced soil liquefaction poses a significant hazard to critical infrastructure and public safety in seismically active regions. The phenomenon of liquefaction occurs when saturated, loose granular soils are subjected to strong ground shaking, leading to a sudden loss of shear strength and stiffness (Seed and Idriss, 1982; Youd *et al.*, 2001). As depicted in Figure 1, the sequence of triggering conditions for liquefaction involves the presence of susceptible soil conditions, high groundwater table, and intense seismic loading. The consequences of liquefaction can be catastrophic, manifesting as excessive settlements, lateral spreading, and bearing capacity failures.

To mitigate the risks associated with liquefaction, various ground improvement techniques have been developed and implemented in practice. Among these techniques, stone columns have emerged as a viable and cost-effective solution for enhancing the performance of liquefiable soils (Priebe, 1991; Baez and Martin, 1995). Stone columns are vertical columns composed of compacted gravel or crushed stone installed using vibro-displacement or vibro-replacement methods (Barksdale and Bachus, 1983). The primary mechanisms by which stone columns mitigate liquefaction include densification of the surrounding soil, provision of drainage pathways for excess pore pressure dissipation, and reinforcement of the soil matrix (Adalier and Elgamal, 2004).

The effectiveness of stone columns in reducing liquefaction potential has been extensively investigated through experimental studies, including centrifuge modelling (Adalier *et al.*, 2003), full-scale field testing (Ashford *et al.*, 2000; Boulanger *et al.*, 1998), and shaking table experiments (Yet *et al.*, 2017; Sasaki and Taniguchi, 1982). These experimental investigations have provided valuable insights into the behaviour of stone column-reinforced ground under various loading scenarios and have supported the development of analytical and numerical models for predicting their performance.

However, despite the growing body of research on stone columns for liquefaction mitigation, there remains a need for a comprehensive review synthesising the current state of knowledge, identifying key

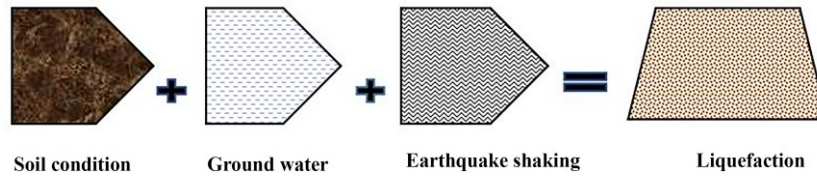


Figure 1. Liquefaction phenomenon showing the sequence of triggering conditions (adapted from info@Americangeoservices.com)

challenges, and outlining future research directions. This review aims to critically assess the mechanisms, application, and limitations of stone columns for liquefaction mitigation by examining evidence from experimental studies, numerical simulations, analytical models, and field case histories. The objectives of this review are to:

- elucidate the fundamental mechanisms governing the performance of stone columns in liquefiable soils
- evaluate the influence of key design parameters, such as area replacement ratio, column spacing, and material properties, on the effectiveness of stone columns
- identify critical challenges and limitations associated with the implementation of stone columns for liquefaction mitigation
- discuss recent advancements, including the use of geosynthetic-encased stone columns (geosynthetic-ESCs), and their potential for enhancing the performance and reliability of the technique
- provide recommendations for future research directions to address knowledge gaps and optimise the design and application of stone columns in seismically vulnerable regions.

By synthesising the existing knowledge and identifying avenues for further investigation, this review contributes to the advancement of stone column technology as a reliable and sustainable solution for liquefaction mitigation. The findings of this review are expected to provide valuable insights for geotechnical engineers, researchers,

and policymakers to enhance the resilience of infrastructure in seismically active areas.

Figure 2 shows the contrast in soil conditions before and after liquefaction. It demonstrates how seismic shaking leads to pore pressure build-up and loss of effective stress, resulting in soil liquefaction.

Mechanisms of liquefaction mitigation by stone columns

Stone columns mitigate liquefaction through three key mechanisms:

1. **Drainage:** The highly permeable stone column material facilitates rapid dissipation of excess pore water pressures generated during seismic events, preventing liquefaction triggering (Adalier and Elgamal, 2004; Seed and Booker, 1977).
2. **Densification:** Vibro-replacement installation methods densify the surrounding soil, increasing its relative density and resistance to liquefaction (Baez and Martin, 1995; Massarsch and Fellenius, 2002).

The densification effect of stone columns is highly dependent on the method of installation. Vibro-replacement methods, in particular, cause lateral displacement and vibration-induced compaction of surrounding loose soil. This increases relative

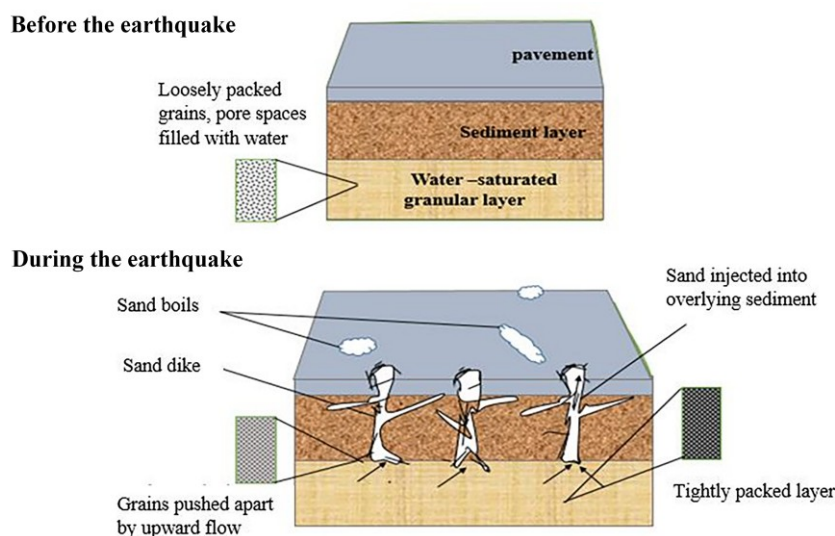


Figure 2. Ground condition before and after soil liquefaction (Obermeier, 1999)

- density and shear resistance, reducing the potential for liquefaction (Massarsch and Fellenius, 2002; Slocombe *et al.*, 2000).
3. Reinforcement: The stone column stiffness and confinement provided by the surrounding soil create an improved composite system with higher shear strength and bearing capacity (Goughnour and Pestana, 1998; Ambily and Gandhi, 2007).

These mechanisms collectively enhance soil properties, reduce excess pore pressures, and improve overall stability of the treated ground, effectively mitigating liquefaction hazards.

Design parameters and installation methods

The steps involved in installing stone columns and how they affect the characteristics of the soil:

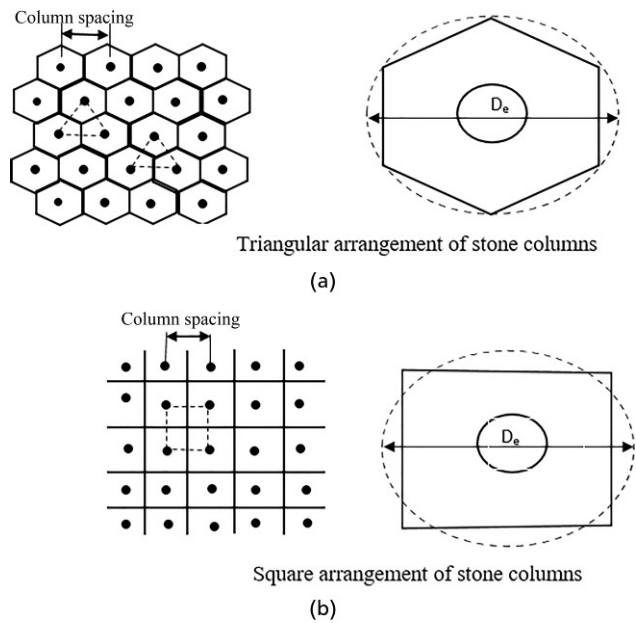


Figure 3. Various patterns of stone columns (IS code 15284: 2003 Part 1)

- installation method (vibro-replacement, vibro-displacement)
- effects on soil properties (densification, increased drainage, enhanced shear strength)
- soil improvements (increased resistance to liquefaction, reduced shear stress, better load distribution).

Column diameter, spacing, and arrangement pattern are among the design characteristics that affect how well stone columns mitigate liquefaction (Baez and Martin, 1995; Priebe, 1991). Columns are typically triangular or square in shape, with diameters ranging from 0.6 to 1.2 m and spacing of 1.5–3.5 m (Adalier and Elgamal, 2004; Barksdale and Bachus, 1983).

The area ratio is used to quantify ground treatment with stone columns. The area ratio is the area of tributary soil divided by the area of stone columns. Usually, an area ratio of 10%–30% is used (Part 1 of IS code 15284:2003). Figure 3 illustrates various patterns of stone columns, including triangular, square, and hexagonal arrangements, as specified in IS code 15284:2003 part 1.

According to IS code 15284:2003 Part 1, the diameter of the circular effect region is 1.128S for square patterns and 1.05S for triangular patterns, where ‘S’ corresponds to the centre-to-centre spacing between granular columns.

Stone column behaviour under different loading scenarios

Table 1 compares the performance of ordinary stone columns (OSCs) and ESCs under static, cyclic, and dynamic loading conditions, summarising their effectiveness in terms of load capacity, settlement, and resilience.

Failure mechanisms of stone columns

Despite their proven effectiveness, stone columns can experience different failure modes during seismic events that may compromise their liquefaction mitigation potential. Common failure mechanisms include bulging, shear failure, and excessive settlement, which is shown in Figures 4 and 5. Bulging failure happens when the surrounding soil’s lateral confining

Table 1. Stone column performance under various loading situations

Loading condition	Performance metric	OSCs	ESCs	Citation
Static loading	Load-bearing capacity	High, influenced by soil and material quality	Higher, more consistent due to geosynthetic support	Barksdale and Bachus (1983)
	Settlement reduction	Effective, variable based on installation	More effective, significant reduction in variability	Ali <i>et al.</i> (2014)
Cyclic loading	Cyclic resistance	Improved, enhances soil density and drainage	Superior, prevents bulging, maintains integrity	Priebe (1991)
	Fatigue resistance	Good, depends on material and compaction	Excellent, due to geosynthetic encasement	Han <i>et al.</i> (2015)
Dynamic loading	Seismic stability	Enhances shear strength, reduces liquefaction	Superior, dissipates energy, reduces settlement	Zhang <i>et al.</i> (2020a)
	Resilience and recovery	Good, maintains load-bearing capacity	Excellent, due to confinement and integrity	Nguyen <i>et al.</i> (2013)

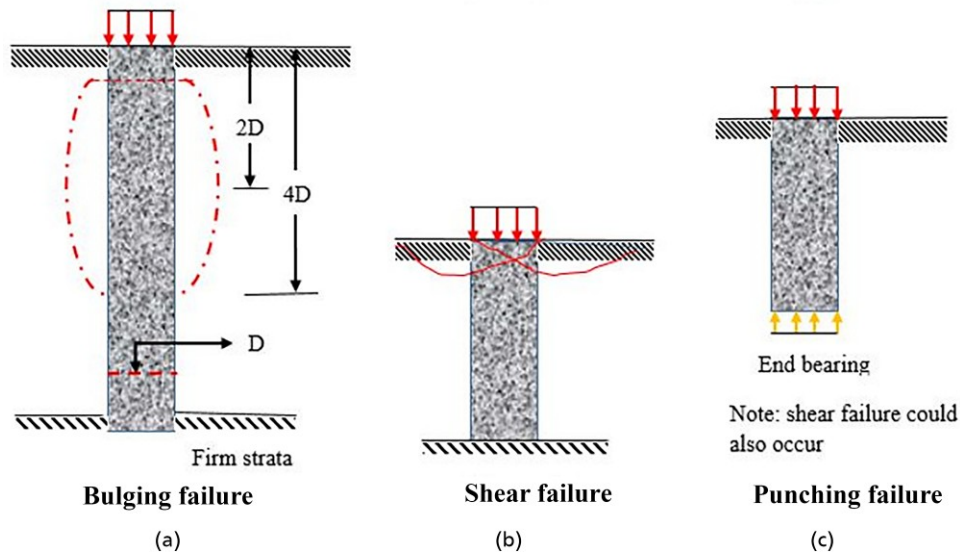


Figure 4. Single stone column failure mechanisms include (a) punching failure, (b) shear failure, and (c) bulging failure (Barksdale and Bachus, 1983)

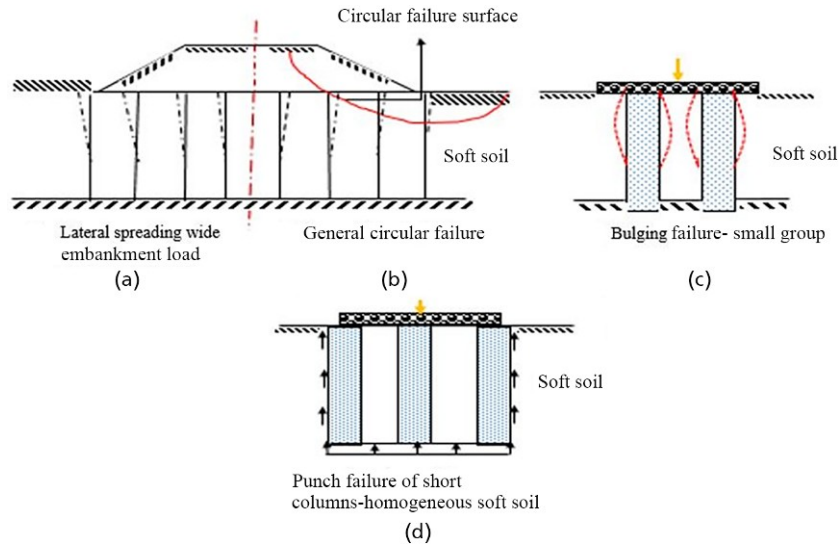


Figure 5. Stone columns can fail in four ways – punching, general circular, bulging, and lateral spreading (Barksdale and Bachus, 1983)

pressure is not enough to stop the stone column's outward deformation (Hughes and Withers, 1974). Soft, cohesive soils with low undrained shear strength are more likely to experience this failure mode.

Furthermore, field case studies have demonstrated that actual earthquakes can cause stone columns to fracture (Hausler, 2002). These case studies highlight the importance of proper design, construction quality control, and post-installation monitoring to

ensure the long-term performance of stone columns for liquefaction mitigation (Boulanger *et al.*, 1998; Slocombe *et al.*, 2000).

Recent advancements: geosynthetic-encased stone columns

Using geosynthetic-ESCs is a novel approach to enhance performance and reduce the disadvantages of traditional stone columns (Murugesan and Rajagopal, 2007; Yoo and Lee, 2012). Geosynthetic-covered stone column is shown in Figure 6.

OSC

- homogeneity affected due to column deformations
- prone to clogging.

ESC

- studied for ground supporting extensively
- increase bearing capacity and lateral load resistance.

The geosynthetic encasements (GECs) also fulfil the role of filter and excluded the soil particles of the surrounding area from entering the stone column (Adalier and Elgamal, 2004; Indraratna *et al.*, 2013). This filtering mechanism keeps the stone column highly permeable and drainage capacity to dissipate additional pore water pressures following earthquake

stress (Murugesan and Rajagopal, 2010). As is evidenced by number of models and studies, especially in soft fine-grained soil, geosynthetic-ESCs exhibit higher effectiveness compared with conventional stone columns. Table 2 provides a comprehensive comparison between OSCs and geosynthetic-ESCs, underscoring the additional support and stability offered by GECs (Keykhosropur *et al.*, 2012; Almeida *et al.*, 2013).

Review of research on stone column applications in liquefaction mitigation

Stone columns are a practical ground improvement technique for lowering liquefaction in seismically active areas. Table 3 summarises

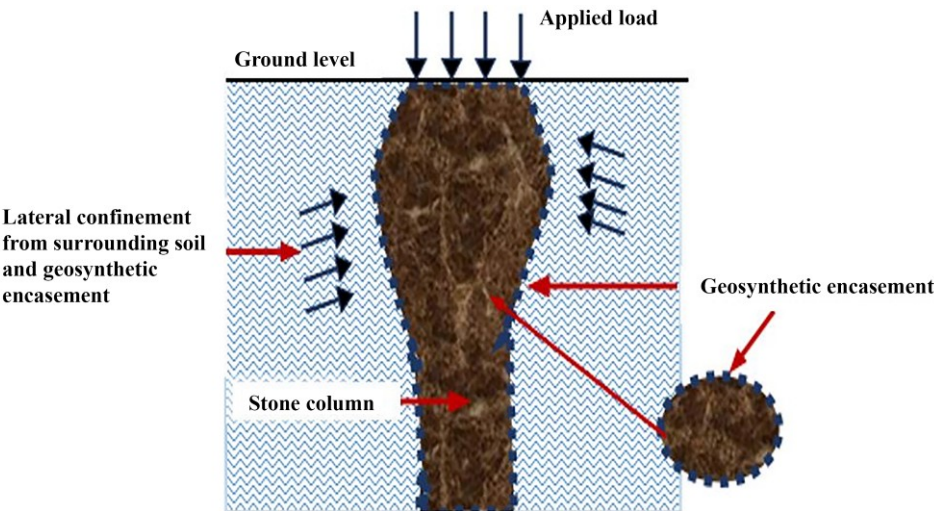


Figure 6. Geosynthetic-covered stone column (Murugesan and Rajagopal, 2010)

Table 2. Comparing the performance of regular stone columns (OSCs) and geosynthetic-encased stone columns (GECs)

Aspect	OSCs, or ordinary stone columns	ESCs, or encased stone columns
Geosynthetic encasement	Not applicable	High tensile strength, durable geosynthetics, properly installed (Zhang <i>et al.</i> , 2020a)
Lateral support	Limited, may require closer spacing (Priebe, 1991)	Enhanced due to geosynthetic encasement (Zhang <i>et al.</i> , 2020a)
Load-bearing capacity	Improved, but variable based on soil conditions (Barksdale and Bachus, 1983)	Superior, consistent performance due to encasement (Zhang <i>et al.</i> , 2020a)
Settlement reduction	Effective, but depends on quality control (Ali <i>et al.</i> , 2014)	Highly effective, significant reduction in settlements (Han <i>et al.</i> , 2015)
Drainage improvement	Good, but can be compromised by material segregation (Castro and Sagaseta, 2011)	Excellent, consistent drainage paths maintained by geosynthetics (Nguyen <i>et al.</i> , 2013)
Installation complexity	Relatively simple, requires quality monitoring (Ali <i>et al.</i> , 2014)	More complex, requires precise installation of geosynthetics (Guetif <i>et al.</i> , 2007)
Cost	Generally lower cost due to simpler installation	Higher initial cost due to materials and installation complexity
Applications	Suitable for a wide range of soils and applications	Particularly effective in soft, liquefiable soils and high-risk seismic areas
Load-settlement behaviour	Exhibits typical load-settlement curve: initial elastic deformation followed by plastic deformation	Superior load-settlement behaviour due to lateral confinement. Reduced settlements and higher load-bearing capacity (Castro and Sagaseta, 2011)
Challenges	Susceptible to performance issues in soft soils without additional support	Requires precise installation and higher costs due to encasement materials (Castro and Sagaseta, 2011)

Table 3. Key aspects of previous research studies on stone columns

Author(s), year	Study type	Study goal	Application and methodology	Key findings	Key parameters
Seed and Booker (1977)	Analytical study	Develop a design method for gravel drains to mitigate liquefaction potential	Analytical solution based on excess pore pressure dissipation	Developed a design method for gravel drains considering the spacing and permeability of drains	Drain spacing, permeability
Stuedlein and Bain (2021)	Analytical	Develop a framework for incorporating uncertainty in liquefaction-induced lateral spreading	Proposed a probabilistic approach for evaluating liquefaction-induced lateral spreading	Highlighted the importance of considering uncertainties in liquefaction assessments	Probability of liquefaction, lateral spread displacement, ground improvement effectiveness
Ben Salem <i>et al.</i> (2017)	Experimental and analytical	To investigate the effectiveness of stone columns as a liquefaction remediation technique	Used 24 case studies with standard penetration test (SPT) and cone penetration test (CPT) performed before and after stone column reinforcement. Analysed densification and stiffening mechanisms	Considering the densification and stiffening effects considerably improve the assessment of liquefaction potential of reinforced soil by stone columns	SPT and CPT penetration resistances, area replacement ratio, shear stress reduction factor
Pal and Deb (2019)	Numerical study	Investigate the long-term performance and durability of stone columns	Numerical simulations considering clogging and repeated seismic events	Provided insights into the potential for clogging and the influence of repeated seismic events on the effectiveness of stone columns	Clogging, long-term performance
Zou <i>et al.</i> (2020)	Numerical study	Develop a 3D plasticity model for coarse-grained soils to simulate the seismic behaviour of stone column–reinforced liquefiable ground	Finite difference analysis using the developed constitutive model	Demonstrated the capability of the proposed model in capturing the complex behaviour of stone columns and the surrounding soil under seismic loading	Constitutive modelling, non-linear strength characteristics
Tang <i>et al.</i> (2016)	Numerical (3D finite element (FE))	Explore mitigation of mildly sloped saturated sand strata using geosynthetic-encased stone columns (ESC)	3D FE analyses using OpenSees	ESC reduced lateral deformation more effectively than ordinary columns; improved with increased geosynthetic stiffness and thickness	Geosynthetic thickness, stiffness, permeability, area ratio
Rayamajhi <i>et al.</i> (2014)	Numerical (3D FE)	Study shear stress distribution for discrete columns in liquefiable soils	3D FE simulations using OpenSees PL	Stone columns attracted more shear stress than surrounding soil, reducing liquefaction potential; stress concentration increased with stiffness	Area replacement ratio, column stiffness, soil properties
Moayed <i>et al.</i> (2010)	Numerical	Study gravel drain pile behaviour under earthquake loading for liquefaction mitigation	2D FE modelling of a case study in Iran using gravel drain piles	Gravel drain piles significantly reduced excess pore pressures and liquefaction potential under earthquake loading	Pile diameter, pile spacing, soil permeability, input ground motion
Taslimian and Noorzad (2024)	Numerical simulation	Investigate non-Darcy fluid flow in stone columns for liquefaction mitigation	2D FE model with non-Darcy flow law	Non-Darcy flow increases excess pore pressures up to 100% compared with Darcy flow; permeability and stone column depth significantly influence mitigation effectiveness	Stone column permeability, diameter, depth; non-Darcy vs Darcy flow
El Sherbiny and Wang (2024)	Numerical simulation	Evaluate stone column strategies for mitigating liquefaction-induced uplift of tunnels	2D and 3D models in PLAXIS with square, triangular, hexagonal column patterns	Stone columns arranged closer to tunnel, with larger diameters, less spacing, and more rows in square pattern provide best mitigation	Stone column diameter, spacing, depth, arrangement pattern
Guler <i>et al.</i> (2014)	Numerical	Analyse effect of geotextile encasement on stone column performance under earthquake loading	3D FE analysis comparing ordinary and geotextile-encased stone columns	Geotextile encasement improves column integrity and reduces system displacements under seismic loading	Geotextile stiffness, column diameter, and spacing
Şahinkaya <i>et al.</i> (2017)	Numerical analysis	Investigate performance of floating stone columns under seismic loads	FE analysis using PLAXIS 2D, varying soil/stone column properties under earthquake loads	Stone columns increase bearing capacity under static and seismic loads. Bearing capacity improves with increasing column depth, diameter, and internal friction angle	Floating stone columns, seismic load, bearing capacity, FE programme

(continued on next page)

Table 3. Continued

Author(s), year	Study type	Study goal	Application and methodology	Key findings	Key parameters
Brennan (2004)	Experimental study	Investigate the behaviour of stone columns in sandy soils using centrifuge tests	Centrifuge tests on reinforced and unreinforced soils	Stone columns effectively reduced excess pore water pressure and settlement during seismic loading	Drainage capacity
Rayamajhi <i>et al.</i> (2015)	Experimental	Investigate the reinforcing mechanisms of soil–cement columns in liquefiable sand	Conducted dynamic centrifuge tests on soil–cement column–improved sand	Identified key reinforcing mechanisms of soil–cement columns in liquefiable sand	Area replacement ratio, column stiffness, input motion characteristics
Zhou <i>et al.</i> (2021)	Experimental	Investigate the liquefaction mitigation mechanisms of stone column–improved ground	Conducted dynamic centrifuge tests on stone column–improved ground models	Identified densification and drainage effects as primary mechanisms for mitigation	Area replacement ratio, soil density, input motion characteristics
Luehring <i>et al.</i> (2001)	Field study	Evaluate liquefaction mitigation using vibro–stone columns and drainage wicks	Over 1000 dry bottom-feed stone columns installed in interbedded sandy and silty soils, pre- and post-SPT/CPT	Treatment objectives met by densification between columns, drainage provided by columns and wicks during construction	Column diameter and spacing, apparent fines content, construction sequence

the foundational studies evaluating stone columns as a liquefaction mitigation strategy, highlighting the key findings and parameters critical to their design and performance.

Insights

The visualisations in Figure 7 present a comprehensive overview of stone column research for liquefaction mitigation. Numerical studies dominate the field, reflecting a reliance on computational modelling to analyse complex soil–structure interactions, while laboratory and in situ testing provide critical empirical validation. When compared with other mitigation techniques (Figure 7(b)), the radar chart reveals that stone columns excel in effectiveness and environmental impact, while maintaining competitive advantages in cost-efficiency, applicability, and construction speed, making them a versatile solution. This synthesis of existing knowledge not only evaluates current advancements but also identifies directions for future research to enhance soil resilience against liquefaction.

Performance studies

Experimental study

The effectiveness of stone columns under controlled conditions that mimic field-scale behaviour has been extensively studied, especially through centrifuge testing (Adalier *et al.*, 2003; Brennan, 2004; Zhou *et al.*, 2021). The study also demonstrated on how key design factors influences threats of liquefaction and level of reduction by stone columns including the column layout and area replacement ratio.

Brennan (2004) showed that the columns effectively reduced seepage pressure and displacement in sandy soil during seismic load through the centrifuge tests. The research also established the finding that among the functionalities of stone columns, sustaining the level of drainage was one of the most important. Zhou *et al.* (2021) reported more recently centrifuge experiments concerning

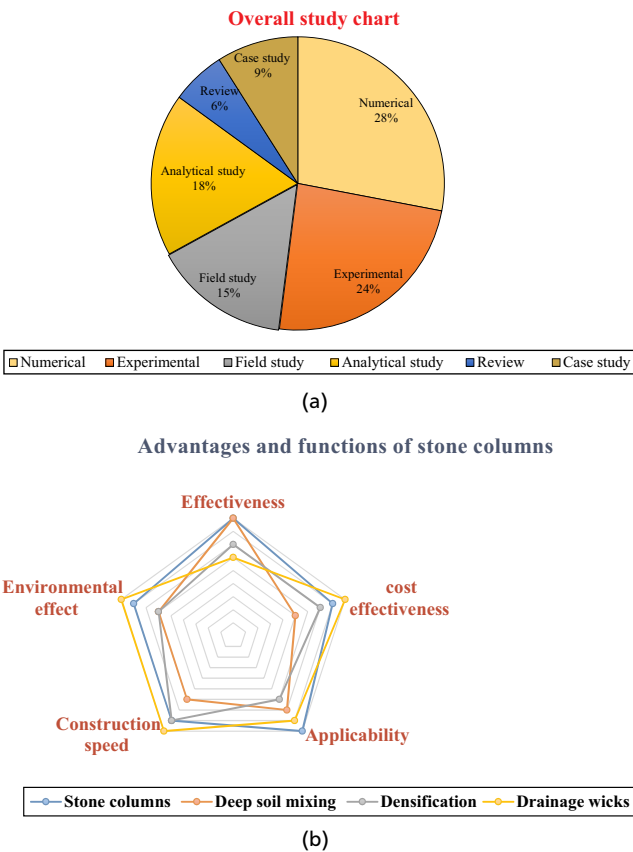


Figure 7. (a) Distribution of study types in stone column research for liquefaction mitigation; (b) comparison of stone columns with other liquefaction mitigation techniques

dense post-improved ground without stone columns, and a dense post-improved ground with stone columns. The analysis of the outcomes substantiated the dominance of the densification effect in controlling post-liquefaction deformation potential (PLDP) as compared with draining influence. The reinforcing effect contributed only a minor improvement to total performance.

Apart from centrifuge test, test using the hollow cylinder apparatus (HCA) has been conducted to investigate the behaviour of the soil elements under cyclic loading condition that characterise the stone column-improved land. Following these tests, Zhang and Wang (2012) performed HCA tests to examine the correlation between the initial static shear stress and the residual volumetric and shear strain of the constituents of the soils. It was observed from the results that the total PLDP is pronounced by the maximal cyclic shear strain of the element soils under cyclic load. This strain may become residual volumetric strain and residual shear strain in case there was an initial static shear stress. Other experimental works have also looked at how different situation affect the extent to which stone column reduces liquefaction. These experimental studies are useful for refining better comparative and predictive design and evaluation methodologies of stone columns, as these studies help furnish essential data on how such systems work for liquefaction countermeasure. Further experiment is needed to understand the efficiency of the soil investigation by stone column in different types of soil, seismicity, and practical conditions. Furthermore, the results must be benchmarked against field case studies and overall long-term performance measurements.

Numerical simulation study

Numerical simulations have become one of the most important methods for evaluating the effectiveness of stone columns also in combination with field investigations and model tests. A number of numerical approaches such as finite element analysis have been applied in order to explain the behaviour of ground reinforced with stone columns under seismic loads. Asgari *et al.* (2013) also performed a detailed numerical analysis to examine the behaviour

of stone columns on reducing the effect of liquefaction of a liquefiable soil layer by employing the finite element-based software called Open Sees PL. A number of parameters, including the nature of the soil, cross-section of the column, and the loading, were evaluated in the study to judge the remedial measure. The outcomes presented showed that stone columns can potentially limit the factors of liquefaction and ground deformation depending on the design inputs and characteristics of the subsoil. In a three-dimensional rheological analysis of a sloping stratum containing stone columns and subjected to liquefaction-induced lateral deformation, Elgamal *et al.* (2009) looked at how this could be achieved using OpenSees PL.

Steps involved in numerical analysis of stone column

Future numerical studies should focus on developing more detailed and complex models that consider complex soil-structure interactions, non-Darcy flow effects, and the influence of various design elements on stone column performance (Taslimian and Noorzad, 2024). Figure 8 outlines the key steps involved in the numerical analysis of stone columns, providing a framework for future research in this area. More dependable and effective numerical tools for the design and analysis of stone column-reinforced ground under seismic loading will eventually result from the encouragement of collaboration between researchers and practitioners to validate and calibrate numerical models against experimental and field data. Table 4 provides a comparison of software used in the numerical simulation of stone column applications for liquefaction mitigation.

Case studies

Case studies help to assess the challenges and real usefulness of stone columns to eliminate liquefaction. Besides, these studies illustrate how effectively stone columns perform for the mitigation of potential liquefaction and the concomitant ground deformations under actual seismicity conditions containing site-specific characteristics.

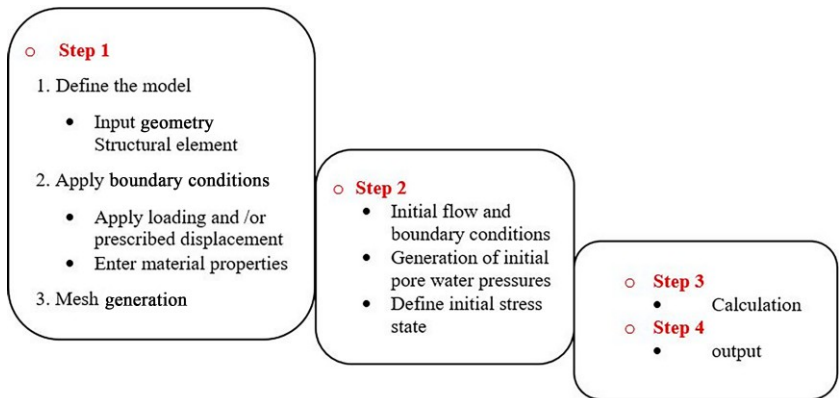


Figure 8. Steps for numerical analysis of stone column

Table 4. Comparison table: numerical simulation software for liquefaction mitigation

Software	Methodology	Key features	Applications	Advantages	Limitations	Studies
PLAXIS	Finite element method (FEM)	Advanced soil models	Stone columns under seismic loading	High accuracy	High computational power	Castro and Sagaseta (2011)
	—	Dynamic/static analysis	Geosynthetic encasement	Detailed modelling	Steep learning curve	—
FLAC	—	Complex geometries	—	—	—	—
	Finite difference method (FDM)	Dynamic analysis	Stone columns	Handles large deformations	Complex interface	Han <i>et al.</i> (2015)
—	—	Customisable models	ESCs	Flexible modelling	High computational requirements	—
	—	Large deformations	Column spacing/diameter effects	—	—	—
ABAQUS	FEM	Comprehensive material models	Soil–column interactions	Robust and versatile	Expensive	Nguyen <i>et al.</i> (2013)
	—	Dynamic analysis	Long-term performance	High scalability	Complex setup	—
OpenSees	—	Scalability	—	—	—	—
	Open-source, FEM-based	Custom material models	Seismic response of stone columns	Highly customisable	Steep learning curve	Zhang <i>et al.</i> (2020b)
—	—	Dynamic analysis	Soil improvement techniques	Strong community support	Less intuitive	—
	—	Earthquake engineering	—	—	—	—

Field observations of stone columns and other enhancing techniques were conducted during 1989 Loma Prieta earthquake in California as described by Mitchell and Wentz (1991). They also detected that stone columns helped to reduce lateral spreads and liquefaction-induced settlements as compared with untreated sites, proving that they were effective in minimising the liquefaction problems. Giving a case of a San Francisco region where the stone columns were put before the Loma Prieta earthquake in 1989, Hausler and Sitar (2001) described that the stone columns effectively reduced the effects of the earthquake. The feasibility of stone columns in post-earthquake situations was observed and it was found that liquefaction failed and drastic ground deformations were prevented in loose, liquefiable sand under the site. Luehring *et al.* (2001) provided documented information on the application of stone columns and drainage wicks at the Salmon Lake Dam in Washington. Liquefiable silt and sand dam foundation in general was improved and surplus pore water pressure was mitigated by stone column–wick drain system. In his paper, Adalier and Elgamal explained how and why Santa Barbara, California’s wastewater treatment plants and Black Sea Georgia’s oil storage facilities should decrease liquefaction with stone columns. These case studies demonstrate how effectively stone columns may be used to increase the saturated sandy soils’ resilience to liquefaction beneath vital infrastructure.

Field study

The effectiveness of stone columns in reducing liquefaction in practical situations can be ascertained through case studies and field research. These techniques also offer an opportunity to assess the long-term behaviour and constructability of stone columns, identify the challenges and limitations that emerge in practical applications, and validate the findings of numerical and experimental investigations.

In one of the earliest field studies ever documented, Engelhardt and Golding (1975) investigated the efficacy of stone columns for liquefaction mitigation at a site in California. The study demonstrated

that stone column–reinforced ground may still achieve enough shear resistance even when the surrounding soil liquefied. The scientists came to the conclusion that the stone columns strengthened the liquefiable soil’s shear strength by acting as reinforcing elements. The effectiveness of improved ground after the 1989 Loma Prieta earthquake in California, including regions restored with stone columns, was thoroughly examined by Mitchell and Wentz (1991). According to the study, locations with stone columns for reinforcement performed better and suffered less damage than the nearby untreated ground.

In conclusion, field research and case studies have demonstrated the effectiveness of stone columns in lowering the danger of liquefaction in real-world situations. Important details regarding the performance, constructability, and long-term behaviour of stone columns have been made public by these studies. More field study is required to determine how effectively stone columns function in a wider range of soil types, seismic events, and field circumstances. Field performance data must be combined with experimental research and numerical simulations to create more accurate and reliable design and evaluation methods for stone column–improved ground. The outcomes of case studies and field research can aid in the optimisation of stone column design and installation in seismically active areas, ultimately leading to the creation of more resilient and sustainable infrastructure.

Comparison of findings of analytical, numerical, and field research, focusing on stone column performance under diverse conditions, is shown in Table 5.

Machine learning and AI in geotechnical engineering

Machine learning models

Machine learning (ML) algorithms have shown promising results in predicting soil behaviour and the efficacy of ground augmentation

Table 5. Comparing analytical, numerical, and field research on stone column performance for liquefaction mitigation

Study type	Key aspects	Advantages	Limitations
Experimental studies	Centrifuge experiments (Zhou <i>et al.</i> , 2021; Adalier <i>et al.</i> , 2003)	Controlled conditions	Simplified soil profiles
	Hollow cylinder apparatus tests (Zhang and Wang, 2012)	Well-defined boundary conditions and loading scenarios	Limited ability to capture field-scale behaviour
	Shaking table tests (Adalier <i>et al.</i> , 2003)	Investigation of fundamental mechanisms	Difficulty in replicating in situ conditions
Numerical simulation studies	—	Development of design guidelines	Scaling issues
	Finite element analysis (Elgamal <i>et al.</i> , 2009)	Investigation of complex soil–structure interaction	Simplified constitutive models
	Finite difference analysis (Asgari <i>et al.</i> , 2013)	Parametric studies	Idealised boundary conditions
	Discrete element modelling (Wang <i>et al.</i> , 2016)	Assessment of long-term performance and durability	Validation against field performance data
Field studies	Advanced plasticity models (Zou <i>et al.</i> , 2020)	Optimisation of design parameters	Computational complexity
	Pre- and post-earthquake investigations (Hausler, 2002; Yasuda <i>et al.</i> , 2012)	Assessment of real-world performance	Limited instrumentation and monitoring data
	Long-term performance monitoring (Adalier and Elgamal, 2004)	Validation of experimental and numerical findings	Variability in soil conditions and earthquake scenarios
	Pore pressure dissipation measurements (Onoue <i>et al.</i> , 1987)	Identification of challenges and limitations	Difficulty in isolating the effects of stone columns
	—	Calibration and validation of numerical models	Limited number of well-documented case histories
Case studies	Performance during actual earthquakes (Mitchell and Wentz, 1991; Hausler and Sitar, 2001)	Insights into real-world effectiveness	Limited number of well-documented case histories
	Design, construction, and performance aspects (Luehring <i>et al.</i> , 2001)	Identification of successful implementation strategies	Site-specific conditions and challenges
	Comparison with unimproved sites (Adalier and Elgamal, 2011)	Lessons learned for future applications	Difficulty in generalising findings to other sites
	—	Demonstration of practical feasibility	Lack of comprehensive instrumentation and monitoring data

techniques such as stone columns. Two often used models are neural networks (NNs) and support vector machines (SVMs).

SVMs have proven their capacity to correctly identify soil types and forecast how well soil stabilisation techniques will work. SVMs’ potential in this area was demonstrated by Wang *et al.* (2016), who used them to forecast soil behaviour for ground improvement.

NNs possess the ability to use deep learning algorithms to process enormous amounts of data and find complex patterns in the link between soil and structure. Zhang *et al.* (2020b) (vertical ESCs in soft soil) used deep learning NNs to anticipate the settlement of stone columns, demonstrating the predictive potential of these systems.

AI tools: Artificial intelligence (AI) methods such as fuzzy logic systems and genetic algorithms (GAs) have been used in geotechnical engineering to manage uncertainties and optimise the construction of stone columns.

GAs: Genetic algorithms, which mimic natural selection, can be used to optimise design characteristics such as depth, diameter, and stone column spacing. The goal of this method is to save expenses

while increasing performance. Liu and Li (2018) demonstrated the efficacy of GAs by optimising the design of stone columns.

Fuzzy logic systems: More adaptable and flexible design criteria must to be incorporated in order to combat the uncertainties in soil conditions and building quality. As a result, stone column performance forecasts are more precise. Fuzzy logic’s advancements and applications in geotechnical engineering were assessed by Alavi and Gandomi (2012).

Regression analysis

Regression analysis, including linear and multiple regression models, has been used to predict settlement and load-bearing capacity in stone column–improved ground.

Linear regression models offer a simple method for comprehending the connections between the design, soil properties, and the stone columns’ ability to support loads. Basha and Babu (2010) predicted the load-bearing capability of stone columns using linear regression.

Using these ML and AI tools, geotechnical engineers can predict, optimise, and understand the performance of stone columns for liquefaction mitigation. Table 6 highlights essential parameters

Table 6. Comparative analysis and applications

Aspect	Machine learning (ML)	AI tools	Regression analysis
Predictive accuracy	High accuracy in predicting complex soil–structure interactions (Zhang <i>et al.</i> , 2020a)	Effective optimisation of design parameters (Liu and Li, 2018)	Good for linear relationships; useful for initial predictions (Basha and Babu, 2010)
Handling non-linearity	Excellent at handling non-linear relationships in large datasets	Capable of optimising non-linear and complex design problems	Limited to linear or slightly non-linear relationships
Data requirements	Requires large datasets for training and validation	Requires well-defined optimisation objectives and constraints	Requires accurate input data; simpler models can be used with smaller datasets
Interpretability	Models can be complex and less interpretable	Genetic algorithms and fuzzy logic systems provide interpretable rules and solutions (Alavi and Gandomi, 2012)	Highly interpretable; easy to understand the influence of individual variables
Adaptability	Adaptive to new data and can improve over time	Flexible and adaptive to changes in design criteria and constraints	Less adaptable to changes in data or design parameters
Applications in geotechnical engineering	Predicting soil behaviour, settlement, and bearing capacity (Wang <i>et al.</i> , 2016; Zhang <i>et al.</i> , 2020b)	Optimising design parameters, handling uncertainties in soil properties (Liu and Li, 2018; Alavi and Gandomi, 2012)	Predicting load-bearing capacity, settlement estimation (Basha and Babu, 2010; Fattah and Qasim, 2016)
Implementation complexity	Requires expertise in ML algorithms and computational resources	Requires knowledge of AI optimisation techniques and computational tools	Simpler to implement; can be done using standard statistical software

and findings on the practical effectiveness of stone columns in mitigating liquefaction-induced issues.

The uses and benefits of ML, AI, and regression analysis approaches in relation to stone columns for liquefaction reduction are contrasted in the following table.

In terms of stone column design and performance assessment, regression analysis, AI, and ML offer a number of benefits. High predictive accuracy and optimisation capabilities are offered by AI tools and ML models, particularly for intricate and non-linear interactions. Even though regression analysis is easier to use and understand, it is still useful for predicting linear relationships.

Difficulties and solutions for stone columns in liquefaction prevention

Even though stone columns have proved effective in lowering the risk of liquefaction, a number of problems still need to be carefully considered and further investigated in order to optimise their performance and reliability. Table 7 outlines common challenges and

corresponding mitigation strategies, including solutions for clogging and settlement issues.

Although stone columns are a useful method for reducing liquefaction, there are some implementation issues. The performance of stone columns can be negatively impacted by bulging, smear zones, clogging, and uneven settlement. Stone columns can be made more effective and stable by being aware of these problems and implementing the necessary mitigating measures, such as careful installation, GEC, suitable material selection, and careful design.

Common failures and challenges

This section gives an overview of the primary reasons why stone columns fail during seismic events, while there are many design, installation, geotechnical, and unanticipated elements that might cause them to break. Stone columns are a practical ground improvement device that can increase bearing capacity, decrease the chance of liquefaction, and improve soil stability in seismically active areas.

Table 7. Comparison table: problems and mitigation strategies

Problem	Cause	Impact	Mitigation strategy	Citation
Clogging	Soil movement, inadequate material selection	Reduced drainage, decreased load capacity	Proper material selection, geosynthetic encasement, regular monitoring	Castro and Sagaseta (2011)
Smear zone	Installation techniques, tool penetration	Reduced permeability, strength reduction	Careful installation, geosynthetic encasement, pre-installation soil treatment	Ali <i>et al.</i> (2014)
Bulging and buckling	Insufficient lateral support, high loads	Reduced load-bearing capacity, stability	Geosynthetic encasement, proper design and spacing	Zhang <i>et al.</i> (2020b)
Differential settlement	Heterogeneous soil, improper design, variable loads	Structural damage	Uniform design, appropriate spacing, consistent installation quality	Barksdale and Bachus (1983)

- Design and installation issues: Inadequate design and installation techniques are among the primary reasons why stone columns fail.
- Excessive pore water pressure build-up: Stone columns may collapse during an earthquake if there is a significant build-up of pore water pressure. Inadequate drainage capacity, which can be caused by clogging, poor material selection, or a high fines content, may hinder the dissipation of excess pore pressure.
- Lateral deformation and bulging: Insufficient lateral support in loose or soft soils can cause excessive lateral deformation and stone column bulging during earthquakes.
- Liquefaction of surrounding soil: During earthquakes, the surrounding soil may liquefy due to large spaces between stone columns or improper handling of liquefiable soil. If the stone columns do not reach the entire liquefiable stratum, the untreated soil may liquefy and cause instability or failure.

To improve the performance and resilience of stone column systems in seismic zones, it is essential to address these potential failure reasons through continuous monitoring, advanced modelling, and adaptive design methodologies. For improved infrastructure safety and successful liquefaction mitigation in seismic regions, it is essential to comprehend and reduce the hazards related to stone column collapse.

Limitations

Despite the abundance of studies on the use of stone columns to reduce liquefaction, some areas that require further study and knowledge gaps have been identified.

- *Limited field-scale validation:* To validate the long-term performance of stone columns under various soil conditions and seismic hazard scenarios, more thorough field-scale investigations are required, as the majority of current studies rely on numerical simulations and small-scale experiments. The validation of experimental and numerical results and the improvement of design approaches are hampered by the absence of thoroughly recorded case histories.
- *Design parameter optimisation:* More study is required to optimise the design of stone columns for various soil profiles, taking into account elements such as column spacing, area replacement ratio, depth of treatment, and combining stone columns with other ground improvement methods. To create solid design standards and maximise the performance of stone columns, systematic parametric studies encompassing a range of soil types, column configurations, and loading situations are required.
- *Long-term performance and durability:* More research is needed to determine the long-term performance and durability of stone columns in liquefiable soils, especially with regard to the possibility of clogging drainage pathways, modifications to the properties of the soil, and the impact of installation effects on the enhanced ground response.
- *Stone column behaviour in sloping ground:* Compared with level ground settings, the performance of stone columns in sloping ground that is susceptible to lateral spreading is less well characterised.

- *Evaluation of post-liquefaction deformations:* It is necessary to develop and validate feasible and dependable techniques for evaluating how well stone columns mitigate liquefaction-induced deformations under a variety of field situations. Although the PLDP hypothesis has showed promise, more research is needed to determine its usefulness.

In addition to facilitating the creation of trustworthy design guidelines and performance evaluation instruments for a range of soil conditions and seismic hazard scenarios, filling these research gaps will help enhance stone column technology for liquefaction mitigation. To improve the performance of stone columns and their practical application, future research should concentrate on these areas. This will increase the infrastructure's resistance to damage caused by liquefaction.

Future research directions

The current understanding of the effectiveness and challenges of stone columns for preventing liquefaction highlights many interesting avenues for future research:

- *Development of comprehensive design guidelines:* Future studies should aim to establish design guidelines that encompass a wide range of factors influencing the effectiveness of stone columns, such as soil characteristics, seismic loading conditions, column configurations, and the impact of slope geometry in areas susceptible to lateral spreading.
- *Long-term performance monitoring and database development:* Validating design and evaluation techniques and determining the long-term durability of stone columns need the creation of an extensive library of field case histories and long-term performance data of sites enhanced by stone columns.
- *Numerical modelling and simulation:* The best use of stone columns in a variety of soil conditions and seismic scenarios can then be facilitated by using the validated numerical models to perform parametric studies and create design charts and tools.
- *Optimisation of installation methods and column materials:* The relative efficacy of various installation techniques (such as vibro-replacement and vibro-compaction) and column materials (such as crushed stone and gravel) under varied soil conditions should be investigated in future research.

The performance and difficulties of stone columns for liquefaction mitigation can be better understood by concentrating on these prospective research avenues. Infrastructure in seismically active areas will eventually become more resilient and sustainable as a result of the development of more precise, dependable, and useful methods for the design and assessment of stone column-improved ground.

Summary and conclusions

This review synthesises findings from diverse studies to assess the performance and challenges of stone columns in liquefaction mitigation. The literature demonstrates that properly designed stone

columns can effectively reduce liquefaction potential by improving drainage, densifying soil, and providing reinforcement. Stone columns belong to a common practice used for mitigating the risks of liquefaction on the ground. Due to the high porosity of these columns, they serve as ideal conduits for drainage. This characteristic ensures that during earthquakes the soil does not have high pore water pressure. They reduce its susceptibility to liquefaction of the ground by enhancing its stability. They reduce lateral spreading and settlement by improving the response of the material of the soil with regard to cyclic loads.

However, challenges remain in optimising designs for various soil conditions, evaluating long-term performance, and characterising installation effects. Future research should focus on developing comprehensive design guidelines, establishing field performance databases, and leveraging validated numerical models to create practical design tools. Collaboration between researchers and practitioners is crucial for advancing stone column technology and addressing knowledge gaps.

By expanding our understanding of stone column behaviour and optimising designs, engineers can more confidently deploy this technology to enhance infrastructure resilience in seismically active regions. While alternative techniques may be suitable in some cases, the continued advancement of stone columns through targeted research and field applications will contribute significantly to mitigating liquefaction hazards and ensuring public safety. This review provides a foundation for future efforts to develop more effective strategies for liquefaction mitigation using stone columns.

Conflict of interest

The authors declare that they have no conflict of interest.

Funding

No funding was provided for this study.

Author contributions

Priyanka Ahirwar: conceptualisation, software work, and writing the original draft. Pradeep Kumar Jain: supervision and reviewing.

Acknowledgements

The facilities provided by Maulana Azad National Institute of Technology, Bhopal, is highly appreciated.

REFERENCES

- Adalier K and Elgamal A (2004) Mitigation of liquefaction and associated ground deformations by stone columns. *Engineering Geology* **72**(3–4): 275–291, [10.1016/j.enggeo.2003.11.001](https://doi.org/10.1016/j.enggeo.2003.11.001).
- Adalier K and Elgamal A (2011) Stone column remediation of liquefiable silty marine foundation deposits. In *Proceedings of the 21st International Offshore and Polar Engineering Conference*. International Society of Offshore and Polar Engineers, pp. 686–691.
- Adalier K, Elgamal A, Meneses J and Baez JI (2003) Stone columns as liquefaction countermeasure in non-plastic silty soils. *Soil Dynamics and Earthquake Engineering* **23**(7): 571–584, [10.1016/S0267-7261\(03\)00070-8](https://doi.org/10.1016/S0267-7261(03)00070-8).
- Alavi AH and Gandomi AH (2012) Predicting the load-bearing capacity of shallow foundations using GMDH-type neural networks and EPR. *Engineering Structures* **33**(6): 1966–1976, [10.1016/j.engstruct.2011.02.021](https://doi.org/10.1016/j.engstruct.2011.02.021).
- Ali SM, Cubrinovski M, Bray JD, Sadeghinejad A and Wotherspoon L (2014) Performance of stone columns in liquefaction mitigation: field observations from Christchurch, New Zealand. *Journal of Geotechnical and Geoenvironmental Engineering* **140**(2): 04013004, [10.1061/\(ASCE\)GT.1943-5606.0001009](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001009).
- Almeida MSS, Hosseinpour I and Riccio M (2013) Performance of geosynthetic encased stone columns in soft clay: numerical and analytical studies. *Geosynthetics International* **20**(4): 252–262, [10.1680/gein.13.00015](https://doi.org/10.1680/gein.13.00015).
- Ambily AP and Gandhi SR (2007) Behavior of stone columns based on experimental and FEM analysis. *Journal of Geotechnical and Geoenvironmental Engineering* **133**(4): 405–415.
- Asgari R, Baghlani A and Ghaffarzadeh H (2013) Seismic performance of stone columns using finite element method. *Soil Dynamics and Earthquake Engineering* **55**: 92–102, [10.1016/j.soildyn.2013.09.015](https://doi.org/10.1016/j.soildyn.2013.09.015).
- Ashford SA, Rollins KM and Lane JD (2000) Liquefaction mitigation using stone columns in silty sands. *Journal of Geotechnical and Geoenvironmental Engineering* **126**(6): 518–527.
- Baez JI and Martin GR (1995) Permeability and shear wave velocity of vibro-replacement stone columns. In *Soil Improvement for Earthquake Hazard Mitigation*. ASCE, pp. 66–81.
- Barksdale RD and Bachus RC (1983) *Design and Construction of Stone Columns: Vol. I* (Report No. FHWA/RD-83/026). Federal Highway Administration.
- Basha BM and Babu GLS (2010) Analysis of load-carrying capacity of stone columns. *Geotechnical and Geological Engineering* **28**: 161–170, [10.1007/s10706-009-9292-6](https://doi.org/10.1007/s10706-009-9292-6).
- Ben Salem M, Benzouak A and Chehat F (2017) Performance of stone columns as liquefaction remediation: a case study approach. *Bulletin of Engineering Geology and the Environment* **76**(3): 1143–1153.
- Boulanger RW, Curras CJ, Kutter BL, Wilson DW and Abghari A (1998) Seismic soil-pile-structure interaction experiments. *Journal of Geotechnical and Geoenvironmental Engineering* **124**(10): 1042–1051.
- Brennan AJ (2004) *Vertical Drains as a Countermeasure to Earthquake-Induced Soil Liquefaction*. Doctoral dissertation, University of Cambridge, [10.17863/CAM.11720](https://doi.org/10.17863/CAM.11720).
- Castro J and Sagaseta C (2011) Deformation and consolidation around encased stone columns. *Geotextiles and Geomembranes* **29**(3): 268–276, [10.1016/j.geotexmem.2010.12.001](https://doi.org/10.1016/j.geotexmem.2010.12.001).
- El Sherbiny R and Wang Z (2024) Liquefaction mitigation around tunnels using stone columns. *Soil Dynamics and Earthquake Engineering* **180**: 107321.
- Elgamal A, Lu J and Forcellini D (2009) Mitigation of liquefaction-induced lateral deformation in a sloping stratum: three-dimensional numerical simulation. *Journal of Geotechnical and Geoenvironmental Engineering* **135**(11): 1672–1682, [10.1061/\(ASCE\)GT.1943-5606.0000137](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000137).
- Engelhardt H and Golding B (1975) Use of stone columns for liquefaction mitigation: case study. *ASCE Specialty Conference on Earthquake Engineering*.
- Fattah MY and Qasim AA (2016) Predicting settlement of soft soil improved by stone columns using regression analysis. *International Journal of Civil Engineering and Technology (IJCIET)* **7**(1): 149–163.
- Goughnour RR and Pestana JM (1998) Mechanical behavior of stone columns under seismic loading. In *Proceeding 2nd International Conference on Ground Improvement Techniques*, pp. 157–162.
- Guetif Z, Bouassida M and Debats JM (2007) Improved soft clay characteristics by stone column reinforcement. *Ground Improvement* **11**(2): 91–102.
- Guler E, Alexiew D, Abbaspour A and Koc M (2014) Seismic performance of geosynthetic-encased stone columns. *Transportation Research Record: Journal of the Transportation Research Board* **2462**(1): 77–88, [10.3141/2462-10](https://doi.org/10.3141/2462-10).
- Han J, Ye S, Oztoprak S and Parsons RL (2015) Numerical analysis of foundation columns to support widening of embankments. *Computers and Geotechnics* **58**: 59–68, [10.1016/j.compgeo.2014.12.002](https://doi.org/10.1016/j.compgeo.2014.12.002).

- Hausler EA (2002) *Influence of Ground Improvement on Settlement and Liquefaction: A Study Based on Field Case History Evidence and Dynamic Geotechnical Centrifuge Tests*. Doctoral dissertation, University of California, Berkeley.
- Hausler EA and Sitar N (2001) Performance of improved ground in the 1989 Loma Prieta earthquake. *Journal of Geotechnical and Geoenvironmental Engineering* **127**(10): 889–902.
- Hughes JMO and Withers NJ (1974) Reinforcing of soft cohesive soils with stone columns. *Ground Engineering* **7**(3): 42–49.
- Indraratna B, Basack S and Rujikiatkamjorn C (2013) Numerical solution of stone column-improved soft soil considering arching, clogging, and smear effects. *Journal of Geotechnical and Geoenvironmental Engineering* **139**(3): 377–394, [10.1061/\(ASCE\)GT.1943-5606.0000789](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000789).
- Keykhosropur L, Soroush A and Imam R (2012) Numerical study on stone columns with geosynthetic encasement. *Geotextiles and Geomembranes* **35**: 61–68.
- Liu H and Li L (2018) Optimization of stone column design using genetic algorithm. *Geotechnical and Geological Engineering* **36**: 3755–3767, [10.1007/s10706-018-0552-4](https://doi.org/10.1007/s10706-018-0552-4).
- Luehring D, Bartz G and Bernard C (2001) Stone columns and wick drains for dam foundation liquefaction mitigation. *Proceedings of the GeoFrontiers Conference 2001*, ASCE.
- Massarsch KR and Fellenius BH (2002) Vibratory compaction of coarse-grained soils. *Canadian Geotechnical Journal* **39**(3): 695–709.
- Mitchell JK and Wentz FJ (1991). *Performance of Improved Ground during the Loma Prieta Earthquake* (Vol. 91, No. 12). National Science Foundation.
- Moayed H, Huat BBK and Mokheri M (2010) Using stone column as a suitable liquefaction remediation in Persian Gulf Coast. *Electronic Journal of Geotechnical Engineering* **15**: 1757–1767.
- Murugesan S and Rajagopal K (2007) Model tests on geosynthetic-encased stone columns. *Geosynthetics International* **14**(6): 346–354, [10.1680/gein.2007.14.6.346](https://doi.org/10.1680/gein.2007.14.6.346).
- Murugesan S and Rajagopal K (2010) Studies on the behavior of single and group of geosynthetic encased stone columns. *Journal of Geotechnical and Geoenvironmental Engineering* **136**(1): 129–139, [10.1061/\(ASCE\)GT.1943-5606.0000187](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000187).
- Nguyen TV, Rayamajhi D, Boulanger RW et al. (2013) Design of DSM grids for liquefaction remediation. *Journal of Geotechnical and Geoenvironmental Engineering* **139**(11): 1923–1933, [10.1061/\(ASCE\)GT.1943-5606.0000932](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000932).
- Obermeier SF (1999) Seismic liquefaction features: examples from paleoseismic investigations in the continental United States. USGS Report, 7.
- Onoue A, Mori N and Takano J (1987) In situ experiment and analysis on well resistance of gravel drains. *Soils and Foundations* **27**(2): 42–60, [10.3208/sandf1972.27.2_42](https://doi.org/10.3208/sandf1972.27.2_42).
- Pal S and Deb K (2019) Effect of clogging of stone column on drainage capacity during soil liquefaction. *Soils and Foundations* **59**(1): 196–207, [10.1016/j.sandf.2018.10.005](https://doi.org/10.1016/j.sandf.2018.10.005).
- Priebe HJ (1991) Vibro-replacement-design criteria and quality control. In *Deep Foundation Improvements: Design, Construction, and Testing*. ASTM International.
- Rayamajhi D, Nguyen TV, Ashford SA et al. (2014) Numerical study of shear stress distribution for discrete columns in liquefiable soils. *Journal of Geotechnical and Geoenvironmental Engineering* **140**(3): 04013034, [10.1061/\(ASCE\)GT.1943-5606.0000970](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000970).
- Rayamajhi D, Tamura S, Khosravi M et al. (2015) Dynamic centrifuge tests to evaluate reinforcing mechanisms of soil-cement columns in liquefiable sand. *Journal of Geotechnical and Geoenvironmental Engineering* **141**(6): 04015015, [10.1061/\(ASCE\)GT.1943-5606.0001298](https://doi.org/10.1061/(ASCE)GT.1943-5606.0001298).
- Şahinkaya F, Vekli M and Çadır CC (2017) Numerical analysis under seismic loads of soils improvement with floating stone columns. *Natural Hazards* **88**(2): 891–917, [10.1007/s11069-017-2897-0](https://doi.org/10.1007/s11069-017-2897-0).
- Sasaki Y and Taniguchi E (1982) Shaking table tests on gravel drains to prevent liquefaction of sand deposits. *Soils and Foundations* **22**(3): 1–14, [10.3208/sandf1972.22.3_1](https://doi.org/10.3208/sandf1972.22.3_1).
- Seed HB and Booker JR (1977) Stabilization of potentially liquefiable sand deposits using gravel drains. *Journal of the Geotechnical Engineering Division* **103**(7): 757–768, [10.1061/AJGEB6.0000735](https://doi.org/10.1061/AJGEB6.0000735).
- Seed HB and Idriss IM (1982) *Ground Motions and Soil Liquefaction during Earthquakes*. Earthquake Engineering Research Institute.
- Slocum BC, Bell AL and Baez JI (2000) The densification of granular soils using vibro techniques. *Ground Engineering* **33**(4): 36–40.
- Stuedlein AW and Bain JA (2021) Probabilistic assessment of lateral spreading mitigation. *Journal of Geotechnical and Geoenvironmental Engineering* **147**(8): 04021062.
- Tang L, Zhang X and Ling X (2016) Numerical simulation of centrifuge experiments on liquefaction mitigation of silty soils using stone columns. *KSCE Journal of Civil Engineering* **20**(2): 631–638, [10.1007/s12205-015-0363-7](https://doi.org/10.1007/s12205-015-0363-7).
- Taslimian R and Noorzad A (2024) Liquefaction mitigation using stone columns with non-Darcy flow theory. *Geotechnical and Geological Engineering* **42**(6): 4375–4399, [10.1007/s10706-024-02785-6](https://doi.org/10.1007/s10706-024-02785-6).
- Wang R, Fu P, Zhang J-M and Dafalias YF (2016) DEM study of fabric features governing undrained post-liquefaction shear deformation of sand. *Acta Geotechnica* **11**(6): 1321–1337, [10.1007/s11440-016-0499-8](https://doi.org/10.1007/s11440-016-0499-8).
- Yasuda S, Harada K, Ishikawa K and Kanemaru Y (2012) Characteristics of ground motion and damage during the 2011 off the Pacific Coast of Tohoku earthquake. *Soils and Foundations* **52**(5): 793–810.
- Yet MN, Oztoprak S and Boulanger RW (2017) Shaking table tests on stone columns in liquefiable sand. *Soil Dynamics and Earthquake Engineering* **97**: 75–85.
- Yoo C and Lee IM (2012) Performance of stone columns with geosynthetic encasement in soft ground. *Geotextiles and Geomembranes* **34**: 1–10.
- Youd TL, Idriss IM, Andrus RD et al. (2001) Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental Engineering* **127**(10): 817–833, [10.1061/\(ASCE\)1090-0241\(2001\)127:10\(817\)](https://doi.org/10.1061/(ASCE)1090-0241(2001)127:10(817)).
- Zhang J and Wang Y (2012) Cyclic loading behavior of saturated sandy soil using hollow cylinder apparatus. *Soil Dynamics and Earthquake Engineering* **43**: 190–198.
- Zhang Y, Chan D and Wang Y (2020a) Consolidation of composite foundation improved by geosynthetic-encased stone columns. *Geotextiles and Geomembranes* **48**(1): 62–69, [10.1016/j.geotexmem.2019.11.004](https://doi.org/10.1016/j.geotexmem.2019.11.004).
- Zhang Y, Chan D and Wang Y (2020b) Consolidation of soft soil improved by vertical geosynthetic-encased stone columns. *Geotextiles and Geomembranes* **48**(2): 170–180, [10.1016/j.geotexmem.2019.11.005](https://doi.org/10.1016/j.geotexmem.2019.11.005).
- Zhou YG, Liu K, Sun ZB and Chen YM (2021) Liquefaction mitigation mechanisms of stone column-improved ground by dynamic centrifuge model tests. *Soil Dynamics and Earthquake Engineering* **150**: 106946, [10.1016/j.soildyn.2021.106946](https://doi.org/10.1016/j.soildyn.2021.106946).
- Zou W, Du Y and Shen S (2020) 3D plasticity model for coarse-grained soils in seismic conditions. *Engineering Geology* **276**: 105751, [10.1016/j.enggeo.2020.105751](https://doi.org/10.1016/j.enggeo.2020.105751).

How can you contribute?

To discuss this paper, please submit up to 500 words to the editor at support@emerald.com. Your contribution will be forwarded to the author(s) for a reply and, if considered appropriate by the editorial board, it will be published as a discussion in a future issue of the journal.