Liquefaction Susceptibility Analysis of Stone Column Improved Ground

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Abstract:

Soil liquefaction is a critical geotechnical hazard triggered by seismic loading, leading to ground instability, settlements, and structural failures. This study evaluates liquefaction susceptibility using Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Shear Wave Velocity (Vs) data, with particular focus on the role of stone columns in mitigation. A total of 22 case studies, including 8 SPT-based, 10 CPT-based, and 4 Vs-based datasets, were analysed under the NCEER (1997) framework. Pre-treatment analyses indicated factors of safety (FS) below unity (0.6–0.9), confirming high vulnerability. Post-treatment results showed notable improvement: SPT blow counts increased by 45–95, CPT resistance by 200–380, and Vs values by 250–320m/s, with FS improving to 1.2–1.8. The findings confirm that stone columns enhance liquefaction resistance through densification, reinforcement, and drainage. The results contribute to advancing practical ground improvement measures in seismic-prone regions.

Keywords: Soil liquefaction, Stone columns, SPT, CPT, Shear wave velocity, Factor of Safety, Ground improvement

1. Introduction:

Soil liquefaction is a major geotechnical hazard induced by seismic loading, where saturated, cohesionless soils lose shear strength and stiffness due to excess pore water pressure buildup. Governed by the effective stress principle, cyclic shaking reduces inter-particle contact forces until effective stress approaches zero, causing the soil to behave like a fluid. In undrained conditions, rapid pore pressure accumulation prevents drainage, leading to sudden strength loss and instability.

Liquefaction susceptibility is influenced by soil type, density, permeability, fines content, groundwater depth, and stress history. Loose to medium-dense sands and silts with high saturation are particularly vulnerable. Seismic factors such as earthquake magnitude, peak ground acceleration (PGA), and duration also play a significant role. Young, loose alluvial or reclaimed soils are more prone compared to older, cemented deposits. These conditions collectively control the cyclic stress ratio (CSR), cyclic resistance ratio (CRR), and factor of safety (FS)

The consequences of liquefaction include ground settlement, loss of bearing capacity, lateral spreading, and flow slides, often damaging lifelines, buildings, and foundations, as observed in the 1964 Niigata and 2011 Christchurch earthquakes. Stone columns are an effective mitigation measure, improving soil density, stiffness, and drainage. This study evaluates liquefaction susceptibility before and after stone column installation to validate their effectiveness in seismic ground improvement.

2. Literature review

Liquefaction evaluation has evolved from early SPT-based methods (Seed & Idriss, 1971; Youd & Idriss, 1997) to integrated approaches combining SPT, CPT, and shear wave velocity (Vs), particularly via the NCEER framework (Youd et al., 2001). While SPT and CPT remain widely used, CPT provides finer resolution for thin liquefiable layers, and Vs methods offer reliable assessment in deeper or layered soils (Andrus & Stokoe, 2000; Kayen et al., 2013). Stone columns are recognized as an effective liquefaction mitigation technique, improving soil density, drainage, and stiffness (Chameau et al., 1991; Madhav & Miura, 1994). Field and centrifuge studies show that treated soils exhibit higher cyclic resistance, reduced pore pressures, and lower settlements under seismic loading (Dobry et al., 1982; Bhattacharya et al., 2017). Recent research highlights the importance of design parameters such as spacing, area replacement, and encasement, which enhance performance and resilience under repeated seismic events (Alshamrani et al., 2023; Yogesh et al., 2025). Numerical models further clarify group effects and long-term stability (Boulanger & Ziotopoulou, 2017).

3. Methodology

This study is based on secondary datasets from 22 published case studies, using SPT, CPT, and Vs data collected before and after stone column installation. Liquefaction susceptibility was assessed following the NCEER (1997) framework. The Cyclic Stress Ratio (CSR) was computed using the simplified Seed and Idriss (1971) procedure:

$$CSR=0.65\cdot(a_{max}/g)\cdot(\sigma_v/\sigma_v')\cdot\gamma_d$$

where a_{max} = peak ground acceleration, g = acceleration due to gravity, σ_v= total vertical stress, σ_v' = effective vertical stress, and γ_d = depth reduction factor.

The Cyclic Resistance Ratio (CRR) was derived from NCEER Report (1997). For soils with fines content FC>35% and index parameter Ic>2.6, the **cyclic softening method** was applied, while for soils with FC<35% and Ic<2.6, the **general liquefaction method** was used. The Factor of Safety (FS) was then calculated as:

$$FS=CSR/CRR$$

Pre- and post-treatment FS values were compared to evaluate the improvement achieved through stone column installation.

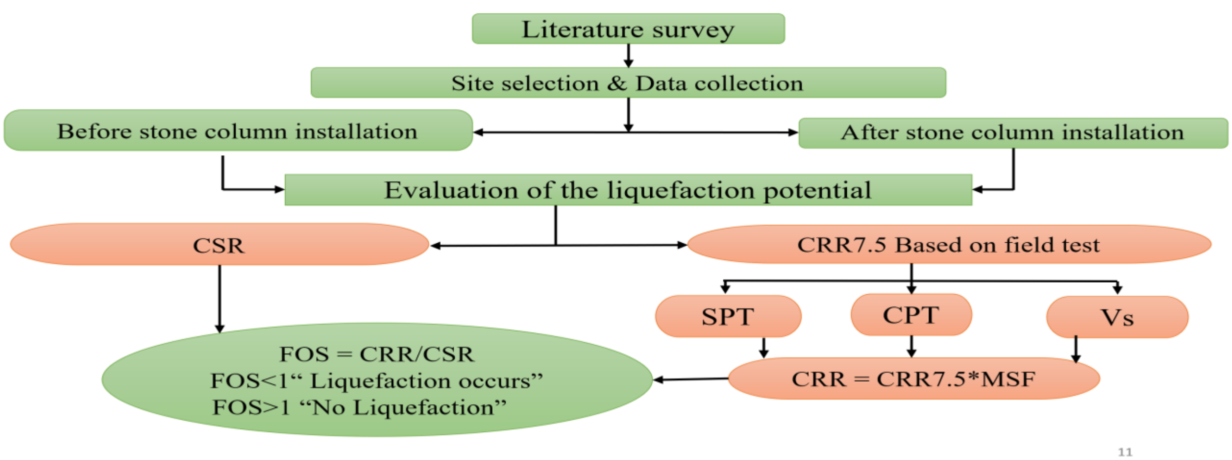


Fig.1 Flow Chart of Liquefaction susceptibility Evaluation Methodology

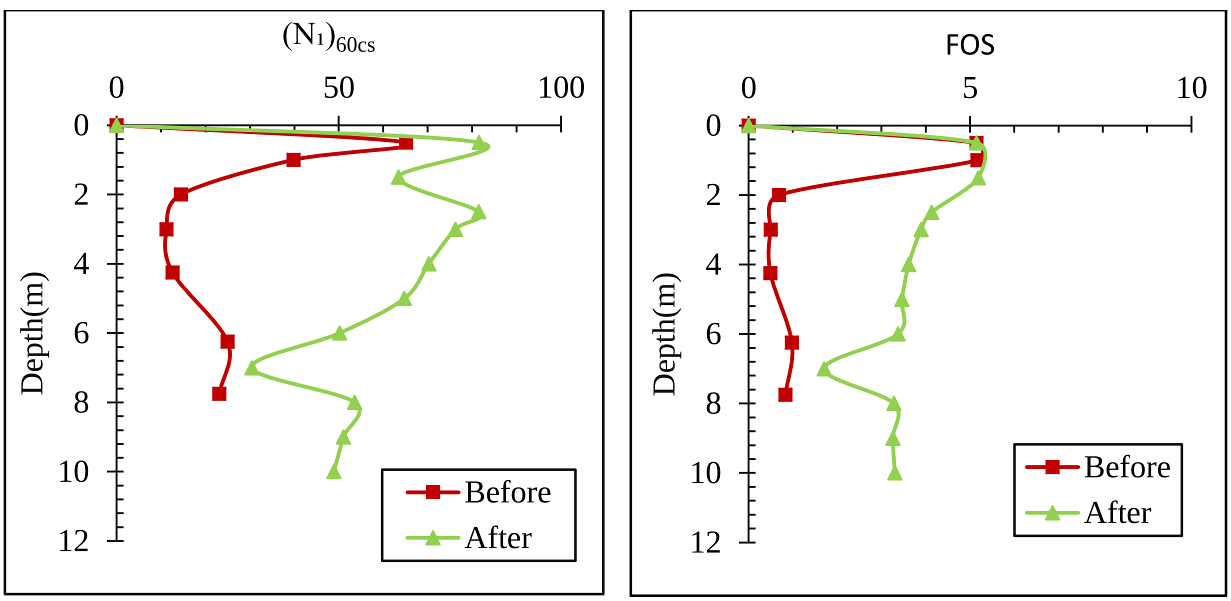
4. Results and Discussion

4.1 SPT- Based Liquefaction Analysis

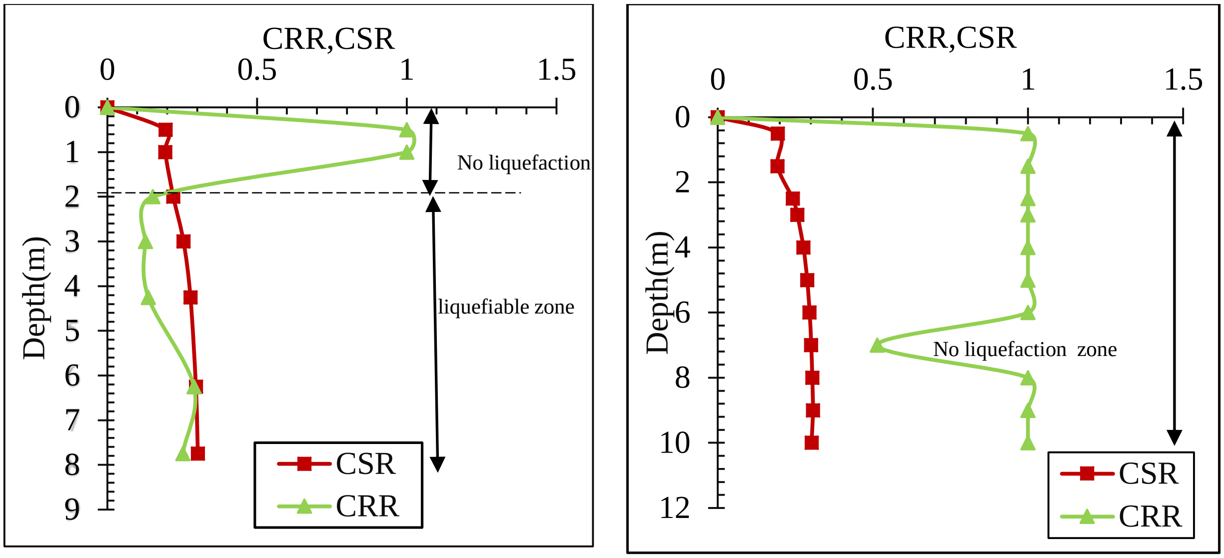
The liquefaction assessment was performed utilizing the SPT-based simplified technique recommended by the NCEER Committee, Idriss and Boulanger (2014):

4.1.1 Case Study 1: Effectiveness of stone columns -field assessment, Aiban (2012)

This study, based on Aiban (2012) in Saudi Arabia's Eastern Province, evaluates the effectiveness of stone columns for liquefaction mitigation. The site comprises loose silty sand and clayey silt with a shallow groundwater table at 1.5–2.0 m, conditions prone to liquefaction under seismic loading. Vibro-replacement was used to install stone columns up to 10 m deep, spaced 2–2.5 m apart. Pre- and post-treatment SPT tests were performed to assess improvements in soil properties. The site's comprehensive SPT data enabled direct liquefaction assessment using the NCEER method (Youd et al., 2001). The site experienced earthquakes with a magnitude of 7.5 and peak ground acceleration of 0.3 g, with the water table at 1.5 m below ground.



(a) **(b)**



(c) (d)

Fig.2 (a) Variation of depth versus $(N_1)_{60cs}$ before and after stone column installation, (b) Variation of depth versus FOS before and after stone column installation. (c)Variation of depth versus CSR & CRR before stone column installation, (d) Variation of depth versus CSR & CRR after stone column installation,

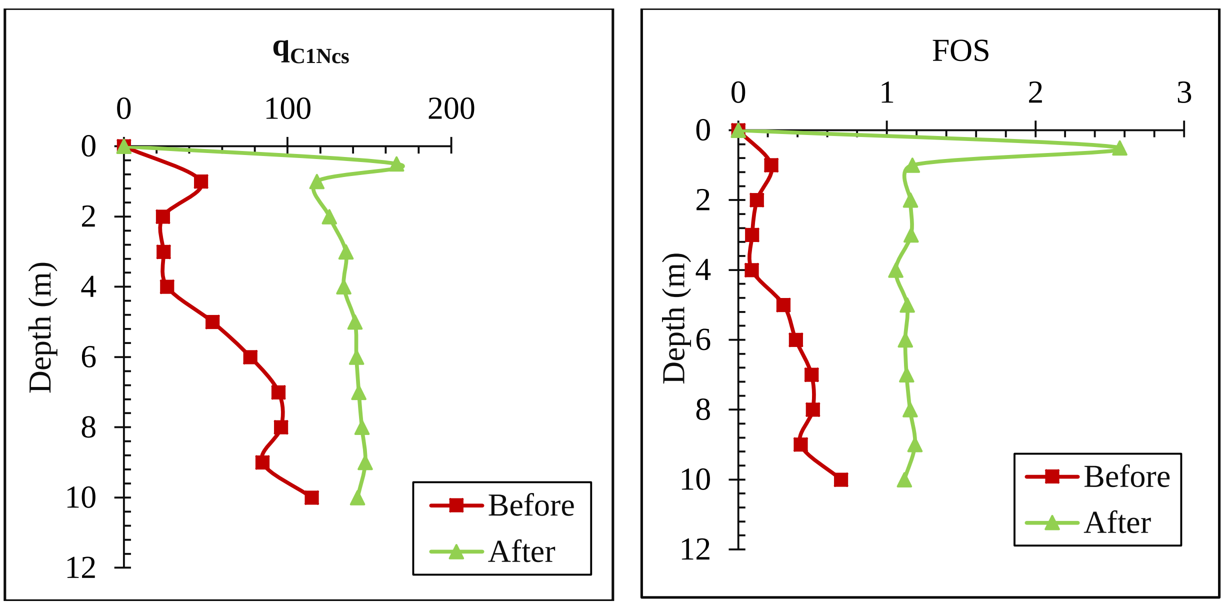
Fig.2 shows the effectiveness of stone columns through a combined analysis of corrected SPT $(N_1)_{60cs}$, CRR, CSR, and Factor of Safety (FOS). Before improvement, low SPT values (15–19) and CRR < CSR up to 8 m depth indicated high liquefaction susceptibility with FOS < 1. After stone column installation, $(N_1)_{60cs}$ increased above 50, CRR exceeded CSR at all depths, and FOS improved up to 6.5, indicating non-liquefiable conditions. The SP-SM soil showed increased density and reduced fines mobility, enhancing cyclic resistance. This demonstrates that stone columns effectively improve soil strength and seismic stability.

4.2 CPT- Based Liquefaction Analysis

The liquefaction assessment was performed utilizing the CPT-based simplified technique recommended by the NCEER Committee, using Robertson and Wride's (1998):

4.2.1 Case Study 1: Stone Column Performance During Seismic Events (Canterbury, New Zealand), Alexander.et al. (2019)

This study, presented by Alexander et al. (2019) at the 7th ICEGE, evaluates ground performance in Canterbury, New Zealand, following major earthquakes in 2010 (Darfield) and 2011 (Christchurch). The site is underlain by interbedded silty sand, sandy silt, and peat, with a shallow water table less than 2 m deep. Loose, saturated layers between 3 and 10 m depth were highly susceptible to liquefaction. To mitigate this, stone columns 7.5 m deep were installed in a triangular layout with 2.1 m spacing. CPT tests and post-seismic field observations assessed the ground performance, while instrumentation monitored seismic response and pore pressure dissipation. The site experienced earthquakes with a magnitude of 6.2 and peak ground acceleration of 0.5 g, with the water table at 1.5 m below ground.



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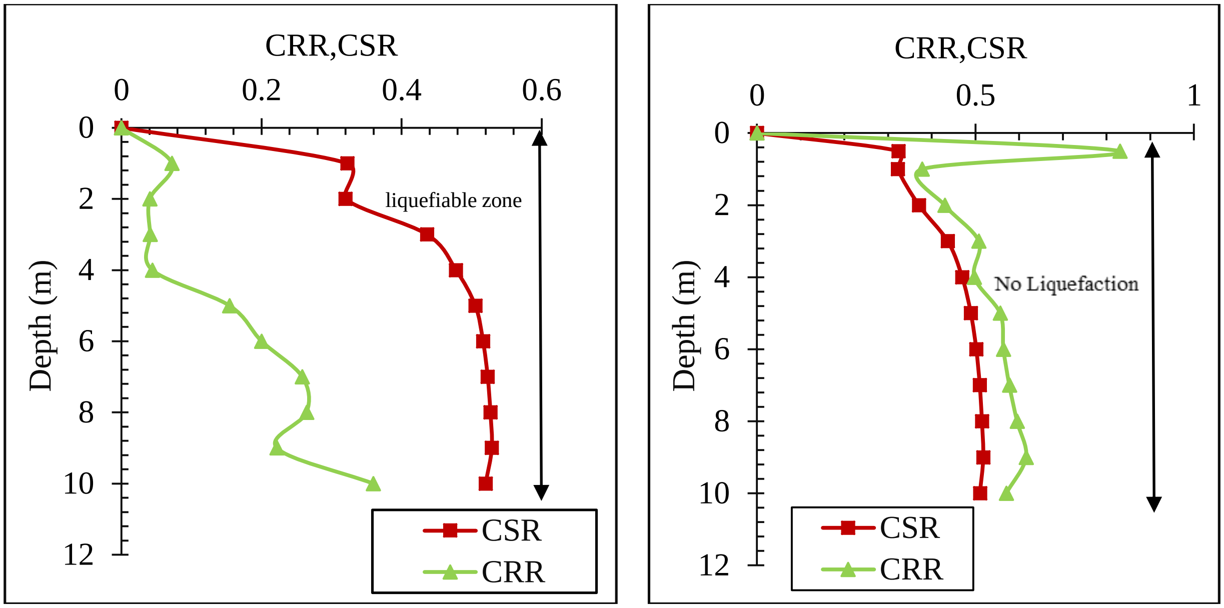


(c) (d)

Fig.3 (a) Variation of depth versus q_{C1Ncs} before and after stone column installation, (b) Variation of depth versus FOS before and after stone column installation. (c)Variation of depth versus CSR & CRR before stone column installation, (d) Variation of depth versus CSR & CRR after stone column installation.

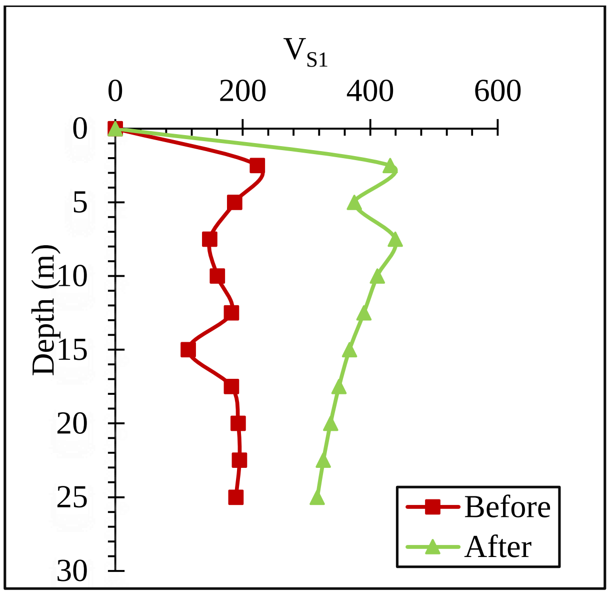
Fig.3 shows improvement in ground behaviour after stone column installation. Initially, low q_{C1Ncs} (<100), high CSR relative to CRR, and FOS < 1 indicated a weak, liquefiable silt-sand profile. After treatment, q_{C1Ncs} exceeded 100, CRR surpassed CSR at all depths, and FOS increased up to 2.3. These gains result from densification, enhanced drainage, and confinement provided by the stone columns, significantly boosting strength, stiffness, and liquefaction resistance, and demonstrating the effectiveness of vibro-replacement for improving lateral pile performance in soft soils.

4.3 Shear wave velocity- Based Liquefaction Analysis

The liquefaction assessment was performed utilizing the Vs-based simplified technique recommended by the NCEER Committee, Andrus and Stokoe's (2000):

4.3.1 Case Study 1: Increase of In-Situ Measured Shear Wave Velocity in Sands with Stone Column Inclusions (Toha, 2017)

This study from Toha (2017) investigated the effect of stone columns and displacement piles on loose to medium-dense sandy soils in Bandung, Indonesia, prone to liquefaction due to shallow groundwater. The site was instrumented using downhole geophysics to measure shear wave velocity (Vs) before and after ground improvement. Within the top 10 m, Vs increased from 120–150 m/s pre-installation to 180–220 m/s post-installation, indicating improved soil stiffness and seismic resilience. Stone columns were installed at controlled spacing and depth to enhance liquefaction resistance. The site experienced earthquakes with magnitude 8.03 and peak ground acceleration of 0.3 g, with the water table at the surface. This profile allowed clear assessment of the impact of stone column inclusion on seismic response parameters.



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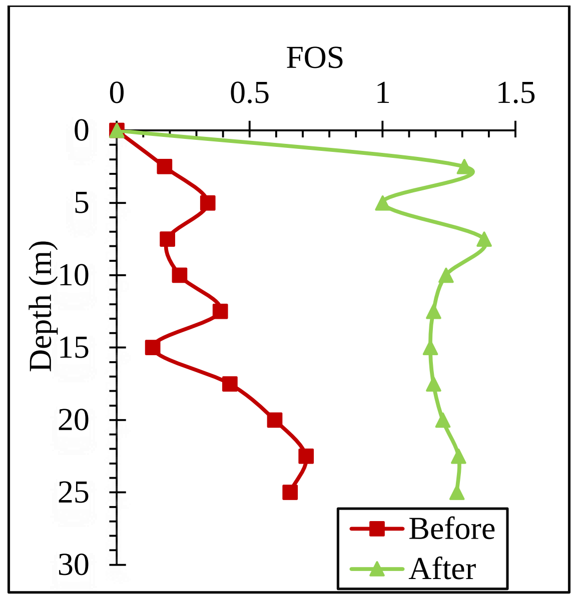

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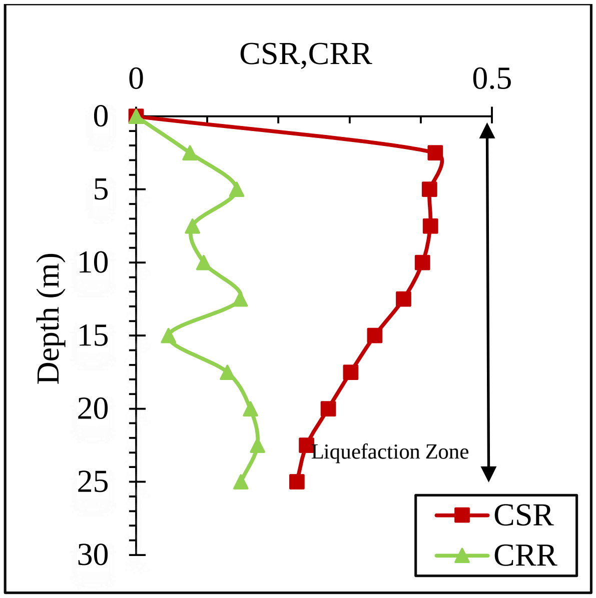

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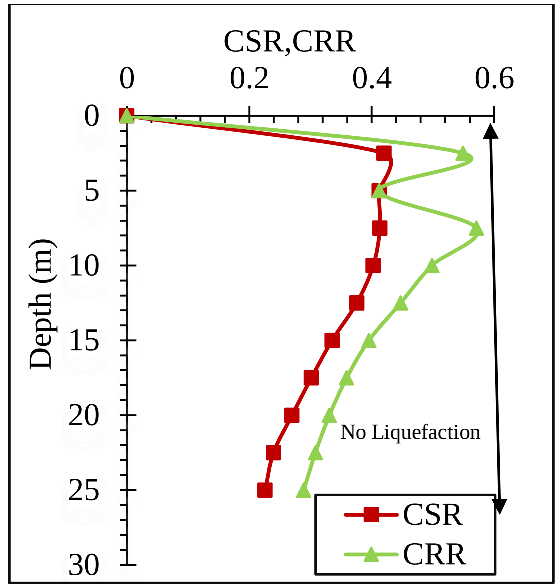

(d)

Fig.4 (a) Variation of depth versus V_{S1} before and after stone column installation, (b) Variation of depth versus FOS before and after stone column installation. (c)Variation of depth versus CSR & CRR before stone column installation, (d) Variation of depth versus CSR & CRR after stone column installation.

Fig.4 clearly show that stone column installation improves soil behavior under earthquake circumstances. A considerable increase in shear wave velocity from 130-230 m/s to 290-385 m/s suggests enhanced soil stiffness, particularly in weak cohesive layers. Prior to treatment, the cyclic resistance ratio (CRR) was continuously less than the cyclic stress ratio (CSR), indicating a high liquefaction potential. After improvement, CRR exceeds CSR over the profile, indicating increased seismic resistance. Furthermore, the factor of safety (FOS) against liquefaction improved from less than 1.0 to greater than 1.2, particularly at depths between 5 and 25 meters. Overall, stone columns enhance dynamic reactivity and effectively reduce liquefaction in soft, fine-grained soil profiles.

4.4 FS Values before and after Stone column installation cross case studies

Table. 1. FS Values Before and After Stone Column Installation Across Case Studies

Case Study / Location	Author(s), Year	Avg FS (Before)	Avg FS (After)
Case 1 – Saudi Arabia	Aiban (2012)	1.2	4.2
Case 2 – Oakland, California	Lee et al. (2005)	1.2	4.8
Case 3 – Washington state, USA	Chen& Bailey (2004)	0.7	5.0
Case 4 – Kigali, Rwanda	Zheng et al. (2025)	0.6	3.0
Case 5 – KUET Campus, Bangladesh	M. I. Hoque and M. Alamgir	0.85	2.7
Case 6 – China	Jie Han &Shulin	0.7	5.5
Case 7 – Rayong province, Thailand	P. Jam Sawang et.al	0.9	5.6
Case 8 – Washington	Barksdale& Bachus (1983)	0.90	2.83
Case 9 – Canterbury, New Zealand	Alexander.et al. (2019)	0.76	2.82
Case 10 – Christchurch, New Zealand	Mahoney, Kupec's (2014)	0.81	3.5
Case 11 – Hinckley Drive Overpass, Utah	Rollins et al. (2012)	0.85	6
Case12 – Pump house enlargement project	Aiban (2002)	0.99	2.86
Case 13 – Bondeno, Province of Ferrara (northern Italy)	Marchi et al. (2022)	0.69	1.4
Case 14 – California, San Francisco Bay	Weaver et al. (2004)	0.9	7.64
Case 15 – Not mentioned	Nguyen et al. (2014)	0.89	2.56
Case 16 – Port of Algiers	Messafer et al. (2020)	0.51	1.34
Case 17 – Jubail industrial City, Saudi Arabia	Hassan A. Abbas (2019)	0.88	2.56
Case 18 – Treasure Island, California	Ashford, S.A., et al. (2000)	0.89	2.78
Case 19 – Bandung, Indonesia	Toha, (2017)	0.48	1.1
Case 20 – Opaoa River, Blenheim	Hendrickson et al.	0.74	1.37
Case 21 – Christchurch, New Zealand	Mahoney& Kupec's (2014)	0.76	1.26
Case 22 – Nanjing, China	Zhou et al. (2017)	0.7	1.17

Table.1 shows the compiled case studies show that ground improvement methods such as vibro-replacement and stone columns effectively increase the factor of safety (FS) against liquefaction. In most locations, the FS improved from less than 1.0 before treatment to values above 2.0 after treatment, with some projects in the USA achieving even higher gains (up to 6–7). Middle Eastern and Asian studies also confirmed consistent enhancements, though the extent varied with soil type and method. Overall, these findings highlight the reliability of ground improvement in mitigating liquefaction risks across diverse geotechnical settings

5. Conclusions

The study evaluated liquefaction susceptibility before and after stone column installation using SPT, CPT, and shear wave velocity (Vs) test data.

Liquefaction risk criteria is summarised based on the analysis of 22 case studies as

1.For the ground with $(N_1)_{60CS}$ less than 15, the risk for liquefaction is high, moderate risk is for sites with $(N_1)_{60CS}$ in between 15-30 and for $(N_1)_{60CS}$ greater than 30, there is no risk for liquefaction.

2.Similialrly based on cone penetration resistance, q_{C1Ncs} the risk for liquefaction is high for the ground with q_{C1Ncs} less than 90, moderate risk is for q_{C1Ncs} in between 90-200, and no risk for liquefaction for the ground with q_{C1Ncs} greater than 200.

3.High risk for liquefaction is observed for the sites with shear wave velocity, V_{S1} is less than 100, moderate risk for V_{S1} in between 100-250 and no risk for sites with V_{S1} is greater than 250.

4. Before treatment, ground resistance in terms of SPT number, cone penetration resistance and shear wave velocity observed are $(N_1)_{60CS}$ <20, q_{C1Ncs} <100, V_{S1}120–150 m/s, and FS < 1.0, which shows high liquefaction potential. After stone column installation, the ground response in terms of all the three filed tests improved in the range of as $(N_1)_{60CS}$ 45 to 95, q_{C1Ncs} from 200 to 380, V_{S1} is improved from 250 to 320 m/s, and FS lies in the range of 1.5–6.0, eliminating liquefaction risk. The improvement is due to increased density, stiffness, and drainage.

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