Global approaches to ground improvement in liquefaction-prone areas: techniques guidelines, and recommendations

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ABSTRACT

This technical review comprehensively explores global practices and advancements in ground improvement techniques aimed at mitigating earthquake-induced liquefaction, focusing on addressing severe liquefaction vulnerabilities. Liquefaction-induced ground instability poses significant challenges, particularly in seismically active regions where it can result in catastrophic damage to infrastructure. The paper examines widely employed methods, such as densification, drainage, lateral stress improvement, grouting, and cementation techniques, alongside recent or new innovative approaches. Furthermore, it reviews international standards and guidelines guiding the ground improvement practices in liquefaction mitigation from the United States, Japan, New Zealand, and Europe. By evaluating the effectiveness, limitations, and sustainability, the review offers practical insights and recommendations for developing resilient and validated solutions to improve ground performance in liquefaction-prone areas. All the liquefaction vulnerability category methods should correlate the different categorisation methods with the final ground deformations including vertical settlement and lateral movements. This paper also discusses two observations from the authors, including the coastal beach sand liquefaction and the sand ejection from stone columns freshly installed or during its installation, then discusses the buoyancy effects and the paradox of drainage functions. The article highlights the promising, environmentally friendly, and cost-effective nature of new emerging technologies, such as IPS and SCRR, while addressing the need for further research and optimization to overcome challenges and ensure practical application in real-world scenarios.

1 INTRODUCTION

Liquefaction, caused by seismic shaking in loose, saturated soils, leads to shear strength loss and structural damage (Seed and Idriss, 1967; Ishihara, 1996), as seen in the 1964 Niigata and 2010-2011 Canterbury earthquakes Zealand (Seed and Idriss, 1967; Bradley and Cubrinovski, 2011). Traditional mitigation techniques like stone columns and grouting target light to medium vulnerability (Tang and Orense, 2014; Schaefer *et al.*, 2017; Taylor, Clayton and Chin, 2021). Recent innovations include MICP and IPS, which offer sustainable alternatives but require further research (DeJong *et al.*, 2022). Subsurface compacted rubble raft (SCRR) has emerged as a viable option for severe liquefaction vulnerability (Du and Shahin, 2016; Du and Xu, 2023). This review examines these techniques, regional standards, and emerging trends, focusing on discussing buoyancy and drainage mechanisms and introducing SCRR technology. It aims to provide insights for practitioners and researchers, emphasizing the importance of comprehensive literature reviews for advancing liquefaction mitigation.

2 GROUND IMPROVEMENT THEORIES, MECHANISMS, AND METHODS

Ground improvement techniques for liquefaction mitigation, implemented globally, are underpinned by shared theoretical foundations and mechanisms (Flora *et al.*, 2023). These core principles comprise key ground improvement processes, including densification, replacement, lateral stress increase, dynamic compaction and vibration, cavity expansion, reinforcement, confinement, Ishihara Crust theory (Ishihara, 1985), and drainage, guiding the development of effective mitigation strategies (Seed and Idriss, 1971; Ishihara, 1996). While the shared theoretical framework provides a common ground, the specific application of these principles may vary considerably across different regions. This is reflected in the diverse range of magnitudes, ranges, and approaches observed in national guidelines and practices. Despite these variations, the shared understanding of fundamental principles and the common objective of mitigating liquefaction risk foster a global framework for addressing this critical geotechnical challenge (Orense, 2015; Wood *et al.*, 2017). This paper focuses on soil replacement, pore-water pressure and buoyancy effects, and drainage formation; other mechanisms are briefly mentioned.

2.1 Soil Densification

Soil densification is a widely utilized ground improvement technique for mitigating liquefaction risk. Methods such as dynamic compaction, vibro-compaction, deep soil mixing, reinforced gravel rafts (Earthquake Commission New Zealand, 2015b), and Subsurface Compacted Rubble Rafts (SCRR) aim to increase soil density by reducing void spaces and enhancing particle interlocking (Du *et al.*, 2023).

2.2 Soil Replacement and Improvement

Soil replacement is a most straightforward technique for mitigating liquefaction susceptibility by replacing liquefiable soils with non-liquefiable materials. This approach is grounded in fundamental geotechnical principles, including principles of dynamic compaction (Sexton and McCabe, 2015).

2.3 Lateral Stress Increase

Ground improvement methods can increase lateral stress, contributing to liquefaction resistance, though its effectiveness is subject to ongoing research (Harada *et al.*, 2010; MBIE, 2021a).

2.4 Dynamic Compaction and Vibration

Dynamic compaction and vibration utilize repetitive, high-energy loads to densify soils, with variations in application reflecting local conditions (Mayne and Jones, 1983; Han, 2015).

2.5 Cavity Expansion Theory (1972)

Cavity Expansion Theory provides a framework for understanding stress redistribution in soil during ground improvement. While not explicitly designed for pile technologies, the principles of cavity expansion can offer valuable insights into the behaviour of driven piles (Yu, 2000), SCRR (Subsurface Compacted Rubble Raft)

(Du and Xu, 2022; Du *et al.*, 2023), and base bearing piles (Qi *et al.*, 2015), Franki piles (Niazi and Mayne, 2013), for predicting bearing capacity, analysing stress distribution, and assessing soil displacement around the installed elements.

2.6 Reinforcement

Reinforcement techniques enhance soil strength and stiffness by introducing materials like geogrids, geotextiles, and fibres (Earthquake Commission New Zealand, 2011; Building Today, 2016; Coghlan, Plomteux and Racinais, 2016; Evans, Ruffing and Elton, 2022).

2.7 Confinement

Confinement methods apply external pressure to restrict soil deformation, including techniques like ground anchors and soil nailing (Shahin, 2015b)(Shahin, 2015a; Schaefer *et al.*, 2017; Patel, 2019).

2.8 Ishihara Crust Theory (1993)

The Ishihara Crust Theory suggests a stable, non-liquefiable layer can mitigate liquefaction effects, influenced by crust thickness and soil properties (MBIE, 2021a; Rateria and Maurer, 2022). Landfill construction offers a unique opportunity to implement the principles of the Ishihara Crust Theory. By carefully selecting and compacting suitable fill materials, engineers can create a substantial, stable layer that effectively acts as an artificial crust, mitigating liquefaction hazards in underlying soils. Furthermore, landfill construction can address flooding concerns in low-lying areas, providing a dual benefit by both mitigating liquefaction risks and improving drainage within the surrounding area, thus addressing the climate challenges (Youd, Hansen and Bartlett, 2002).

2.9 Pore-water pressure and buoyancy effects

While extensive research has focused on the role of elevated pore-water pressure in triggering liquefaction (Seed and Idriss, 1967; Pichler *et al.*, 2012; Fontana *et al.*, 2019), recent studies have highlighted the significance of buoyancy forces in this phenomenon. Clément et al. (2018) introduced a new mechanism for liquefaction, emphasizing the role of buoyancy forces in inducing soil liquefaction, particularly in well-compacted soils where significant pore pressure rise may not always occur.

This concept resonated with observations by the authors. In 2013, during a personal observation at New Brighton Beach, Christchurch, a simple yet insightful phenomenon was witnessed. Upon repeatedly stamping the author's feet on the wet beach sand, a localized liquefaction was observed in the surface layer (approximately 0-20 cm deep). While significant pore pressure increase within this shallow depth was unlikely, the repeated stamping induced particle rearrangement, reducing interparticle contact. This reduction in contact diminished the effective stress within the soil mass, allowing buoyancy forces to dominate, effectively "floating" the sand particles and leading to liquefaction.

If buoyancy forces significantly contribute to liquefaction, it raises questions about the sole reliance on drainage improvement techniques for mitigation. While drainage systems effectively reduce pore water pressure, their effectiveness in mitigating liquefaction may be limited if buoyancy forces play a dominant role. This suggests that a more holistic approach to liquefaction mitigation is required, considering not only pore pressure reduction but also strategies to enhance soil strength and stiffness to resist buoyancy-induced liquefaction. This raises questions about the effectiveness of drainage mechanisms in mitigating liquefaction, as the primary focus of these methods is to reduce pore water pressure.

2.10 Drainage Formation and Liquefaction Mitigation

Drainage techniques, such as vertical drains and prefabricated vertical drains (PVDs), rely on the principles of consolidation theory to dissipate excess pore water pressure during cyclic loading (Ishihara, 1996; Rollins *et al.*, 2021; Evans, Ruffing and Elton, 2022). These techniques aim to accelerate the rate of pore water dissipation, reducing the liquefaction potential. National guidelines recommend varying spacing of drains, installation methods, and drainage material specifications to accommodate differences in soil permeability and groundwater levels.

The effectiveness of drainage techniques in liquefaction mitigation can be influenced by various factors. For instance, drainage features like stone columns or rammed aggregate piers (RAPs) can, under certain conditions, create pathways for the rapid upward flow of liquefied soil, a potential paradox as illustrated in Figure 1. This highlights the complex interplay between drainage and liquefaction behaviour, demonstrating that unintended consequences can compromise mitigation efforts. Alexander et al. (2019) documented cases where liquefied sand boils infiltrated and contaminated stone columns during an earthquake, compromising their performance. Furthermore, long-term performance can be affected by clogging and degradation. Alexander et al. (2019) also reported instances where stone columns failed to adequately mitigate liquefaction due to limited drainage capacity over time, emphasizing the importance of considering long-term performance and potential degradation mechanisms in drainage-based ground improvement systems.

Figure 1: Paradox of drainage: Liquefaction occurrence at a RAPs installation site in Christchurch, 2023.

3 RECENT SOIL IMPROVEMENT TECHNIQUES AGAINST LIQUEFACTION

Numerous soil improvement techniques have been developed to mitigate the risks associated with liquefaction. These traditional techniques, such as densification (e.g., dynamic compaction, vibro-compaction) (Shi, 2004), drainage (e.g., vertical drains, sand drains) (Thevanayagam *et al.*, 2006), reinforcement (e.g., geogrids and ground anchors) (Maulana *et al.*, 2018), and confinement (e.g., soil nailing), aim to improve soil properties and enhance resistance to liquefaction. Selecting a specific technique depends on various factors, including soil type, site conditions, project budget, and the feasibility of implementation. This section focuses on recent techniques, particularly Subsurface Compacted Rubble Raft (SCRR) Technology.

3.1 Subsurface Compacted Rubble Raft (SCRR) Technology

Subsurface Compacted Rubble Raft (SCRR) is a novel patented proprietary ground improvement system (New Zealand Patent No. 728889) that involves the construction of thick manmade strata / crust made of rubble spheres at a depth generally below 3m with a standard thickness of 4 ~ 6 m. Then a standard foundation can be constructed on the ground above, ready to raise a new house. SCRR method is quick to construct and can be done at any time of the year (Du, 2018).

The outstanding strengths of SCRR is that treatment can directly target problematic horizontal geological layers at multiple depths at any location. SCRR method uses clean-fills as primary materials to construct the rafts, so the cost is low and environmental benefits are considerable. Also, no dewatering or excavation is required for the construction, and they typically have a short construction period (Du and Xu, 2023).

The SCRR technology was successfully piloted and peer-reviewed in July 2024, where it upgraded previously red-zoned land to TC2, with high potential to achieve TC1.

3.1.1.1 SCRR Construction method

SCRR rafts are constructed by professional contractors using specialist equipment (Fig. 2), who are experienced in similar piling technologies, such as, Stone Column, Frankipile, Rapid Aggregate Piers, and surface gravel raft foundations. The construction may use one of three methods: dynamic compaction, vibratory compaction, and hydraulic press-in method. Vibratory compaction method uses high vibratory energy forming a sizeable firm rubble sphere of 1 to 1.5 m and a densified soil sphere about 2.5 m in diameter (Fig. 2) (Du and Xu, 2023; Du *et al.*, 2024).

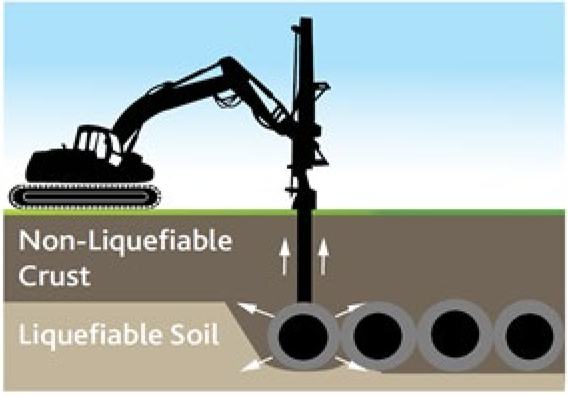

Figure 2: Subsurface Compacted Rubble Raft construction (side view)

3.1.1.2 Mechanisms of SCRR rafts

Ground improvement methods utilise one or a combination of five principal mechanisms to improve the ground's resistance to liquefaction and improve seismic performance: Replacement; Densification; Solidification; Reinforcement; Drainage. SCRR rafts help to limit the amount and consequences of future liquefaction by:

- Replacing the soil with rubble through displacing the soil away simultaneously filling the void with rubble under vibratory compaction at depth, the displaced soil to be densified against surrounding soil,
- Densifying the soil through vibration and also pushing soil by introducing rubble/gravel under high pressure into the soil
- Reinforcing the soil creating a stiff composite rubble/soil mass (Fig. 3).
- Drainage installation to mitigate liquefaction potential, such as vertical drains formed at the end of each installation of SCRR sphere where the casing hole can be filled with engineered materials with sufficient porosity to release the water pore pressure if required (Du *et al.*, 2023).

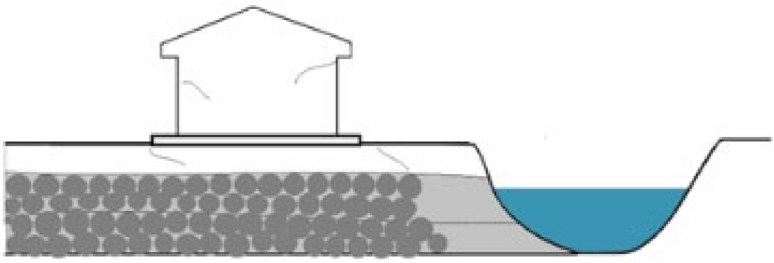

Figure 3: Typical triangular grid installation pattern (Side view)

By achieving this, the non-liquefying soil CRUST is dramatically thickened and stiffened to reduce the likelihood of undulations, tilt and uneven ground surface subsidence, especially lateral movements from liquefaction of the underlying soil layers, therefore reducing damage to the foundations and above buildings (Du *et al.*, 2023).

3.1.1.3 Pilot Project results

The pilot project, sponsored by Callaghan Innovation, successfully demonstrated the effectiveness of SCRR in mitigating liquefaction risk within the Christchurch "red zone."

Key Findings:

- **Successful TC2 Upgrading:** The project successfully upgraded the site from TC3 (high liquefaction risk) to TC2 (moderate risk), meeting MBIE (2021) requirements.
- **Significant Ground Improvement:** SCRR installation resulted in a 104% increase in CPT tip resistance and significant reductions in post-installation liquefaction parameters: 40% reduction in vertical settlement, 84% reduction in lateral movement.
- **Enhanced Lateral Stability:** The unique SCRR framework effectively reduced lateral movement by 85-95%, surpassing the performance of traditional methods.

These findings demonstrate the potential of SCRR as a viable and effective ground improvement technique for mitigating liquefaction risk in high-risk areas.

4 GROUND IMPROVEMENT TECHNIQUES FOR SEVERE LIQUEFACTION MITIGATION

This section aims to recommend ground improvement technologies for addressing severe liquefaction problems. The evaluation is based on key criteria such as cost, technical implementation, scalability, and environmental impact.

4.1 Severe Liquefaction

Severe liquefaction, characterized by significant ground instability and infrastructure damage, was exemplified by the widespread destruction during the 1964 Niigata earthquake (Seed and Idriss, 1967). In such cases, buildings may tilt, sink, or collapse, and underground utilities suffer damage from ground movement, including lateral spreading (CERA, 2016; MBIE, 2021a). Severe liquefaction is typically associated with specific site conditions, such as thick liquefiable soil layers, high groundwater levels, proximity to earthquake epicentres, and locations near slopes or free faces (MBIE, 2021a). This paper focuses on these severe scenarios, which pose the greatest risks. The Christchurch red zones in New Zealand, classified as Technical Category 3 land (Table 1), are a prime example, experiencing extensive damage due to large-scale ground movements, particularly lateral spreading (MBIE, 2012a, 2021a; CERA, 2016).

Table 1: Reproduction of table A4.1 MBIE (2012b) *site criteria and table 3 of* (Soil & Rock Consultants, 2016) *based on calculated SV1D Criteria to the top 10 m of the soil profile. Red Zoned site is an addition to the table.*

Criteria		SLS Calculated SV1D (mm)	ULS Calculated SV1D (mm)	Expected ULS Global Lateral Movement (mm)
TC1		0 -15	0 - 25	Nil
TC2		15 - 50	25 - 100	<100 (Minor)
TC3 criteria	TC3 hybrid	15 - 50	>100	<100 (Minor)
	TC3 SLS<100 mm	50 - 100	>100	100 – 300 (Minor to Moderate
	TC3 SLS>100 mm	>100	>100	300 – 500 (Major)
Red Zoned site		Continuous TC3 land sections with infrastructure severely damaged, which are infeasible to remediate with current techniques.		

There is no universally accepted definition of severe or high liquefaction vulnerability. In this paper, liquefaction is considered severe if it results in ground movement exceeding 100 mm for vertical settlement or lateral displacement during an Ultimate Limit State (ULS) event.

4.2 Comparative Analysis of Technologies

The comparison of the ground improvement technologies is presented in Table 2:

Table 2: Comparison of the ground improvement technologies.

Technology	Cost	Technical Implementation	Scalability	Environmental Constraints
Dynamic Compaction	Moderate (Montgomery, 2002)	Effective for shallow, granular soils (Sieradzki *et al.*, 2013)	Scalable, urban areas	Minimal environmental impact, noise (Bo *et al.*, 2009; Sieradzki *et al.*, 2013)
Vibro-compaction	Moderate (Andrus and Chung, 1995)	Effective for granular soils, deep treatment	Highly scalable	Minimal environmental impact, vibration (Kirsch and Kirsch, 2016)
Soil Mixing	High	Effective for granular and cohesive soils	Localized, high cost	Potential contamination, slurry disposal mixing (Andrus and Chung, 1995; Evans, Ruffing and Elton, 2022).
Subsurface Compacted Rubble Raft (SCRR)	Low to moderate to	Sustainable, waste-reduction, robust solution	Highly scalable	Environmentally friendly, recycling waste (Du and Xu, 2023).

Subsurface Compacted Rubble Raft (SCRR) technology is highly recommended for large-scale liquefaction mitigation projects due to its scalability, cost-effectiveness, and sustainability. Vibro-compaction is also an excellent option for granular soils. Soil mixing and ground freezing suit more localized, high-risk areas but come with higher costs and environmental impacts.

5 GUIDELINES AND STANDARDS FOR GROUND IMPROVEMENT

5.1 United States: ASTM Standards

The American Society for Testing and Materials (ASTM) provides guidelines, such as GTJ10390 for Liquefaction Testing of Layered Sand-Gravel Composites, ASTM D7382 for soil densification verification. ASTM also details criteria for verifying the effectiveness of grouting, compaction, and other improvement methods, emphasizing post-treatment testing to validate soil stability (ASTM, 2020).

NCEER has developed widely referenced models that assess liquefaction triggering and estimate ground deformation, which includes both settlement and lateral spreading (Youd and Idriss, 2001; Jefferies and Shuttle, 2011). The 2015 study by Maurer and Green (2015b) evaluates liquefaction damage indices, finding inconsistencies in the original LPI. It proposes modified indices (LPIISH, LSN) and advocates for an objective, standardized, and cost-effective approach using ROC analysis to improve their predictive accuracy.

5.2 Japan: JGS Standards and Methodologies

The Japanese Geotechnical Society (JGS) mandates testing protocols, including seismic simulations for ground improvement sites. Japan's experiences with large-scale liquefaction have driven the development of sophisticated standards, particularly for urban redevelopment areas. Field monitoring is continuous, with sensors tracking soil response during and after treatment (Toprak and Holzer, 2003).

In assessing liquefaction vulnerability, Japan employs the Liquefaction Potential Index (LPI), developed by Iwasaki et al. in 1978 (Earthquake Commission New Zealand, 2015a).

5.3 European Standards: Eurocode 7 and 8

Eurocode 7 outlines guidelines for ground improvement across Europe, emphasizing safety and performance criteria for bearing capacity, settlement, and liquefaction mitigation. The code allows for regional adaptations, with countries like Italy and Greece implementing supplementary measures for areas with high seismic activity (Potts, 2003; Bond, 2011; Ching and Schweckendiek, 2021).

Eurocode 8 provides guidelines for designing buildings and infrastructure in European seismic zones, addressing the liquefaction potential and expected deformation of soils (The European Union, 2004).

Although Eurocode 8 does not prescribe specific mm values for settlement and lateral movement, it classifies soil based on seismic response (soil types A to D, with D being most vulnerable). For liquefiable soils, Eurocode 8 suggests using detailed site investigations and numerical modeling.

5.4 New Zealand: NZGS and MBIE Guidelines

Following the Christchurch earthquakes, New Zealand developed guidelines under the New Zealand Geotechnical Society (NZGS) and Ministry of Business, Innovation, and Employment (MBIE). These standards emphasize rigorous post-construction testing, including cone penetration tests (CPT) and standard penetration tests (SPT), and outline adaptive measures for project-specific challenges (MBIE, 2015, 2021b).

New Zealand’s Technical Categories (TC1, TC2, and TC3) are particularly influential and widely referenced due to the country's comprehensive response to liquefaction following the 2010-2011 Christchurch earthquakes (MBIE, 2012a).

5.4.1 New Zealand’s Liquefaction Technical Categories (TC1, TC2, and TC3)

The TC system (MBIE, 2012a) divides land into three main categories (Table 1) based on the potential for liquefaction-induced damage.

5.4.2 Guidelines for Post-Treatment Reclassification

After ground improvement measures are applied to liquefiable zones, reclassification is necessary to verify the effectiveness of remediation. New Zealand's guidelines provide a structured approach to post-treatment evaluation and re-categorization.

6 CONCLUSIONS AND RECOMMENDATIONS

This review has examined a wide range of ground improvement techniques employed globally to mitigate the risks posed by earthquake-induced liquefaction. The field has seen significant advancements from traditional methods like densification and drainage to emerging innovations such as MICP and SCRR.

While these techniques offer promising solutions, challenges remain. The effectiveness of many techniques can be influenced by site-specific conditions, the magnitude and duration of seismic events, and the long-term performance of the ground improvement materials.

Furthermore, the review highlights the need for a more comprehensive understanding of the underlying mechanisms of liquefaction, including the role of buoyancy forces and the complex interactions between different ground improvement techniques.

Recommendations

- **Continued Research and Development:** Ongoing research is crucial to refine existing techniques further and develop innovative solutions that are more effective, efficient, and sustainable. This includes:
- **Collaboration and Knowledge Sharing:** Fostering collaboration between researchers, engineers, and policymakers to share knowledge, best practices, and innovative solutions.

- **Addressing the Challenges of Severe Liquefaction:** Developing and implementing effective mitigation strategies for severe liquefaction scenarios, including those involving large-scale ground deformations and complex site conditions.
- **Integrating Sustainability Considerations:** Prioritizing the development and implementation of environmentally sustainable ground improvement techniques that minimize environmental impacts and maximize resource efficiency.

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